Improving Neutrino Energy Reconstruction with Machine Learning

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Margot MacMahon

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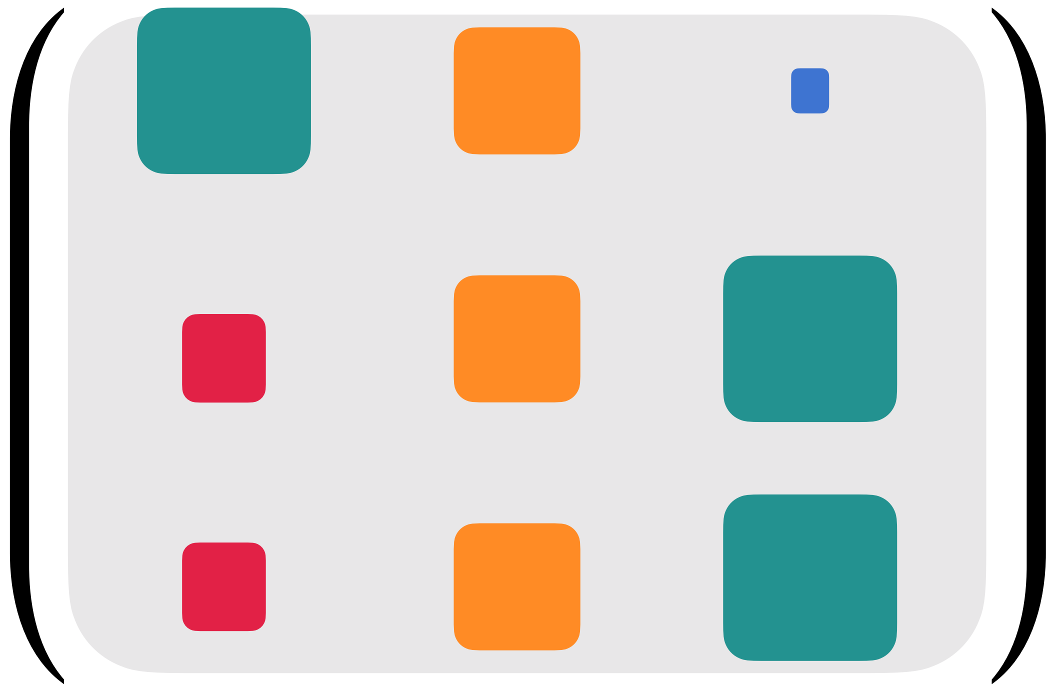
8-11th April 2024

Overview

- Neutrino oscillation measurements
- Neutrino - nucleus interactions
- Our network
- Results
- Conclusions

Neutrino Oscillation Measurements

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$



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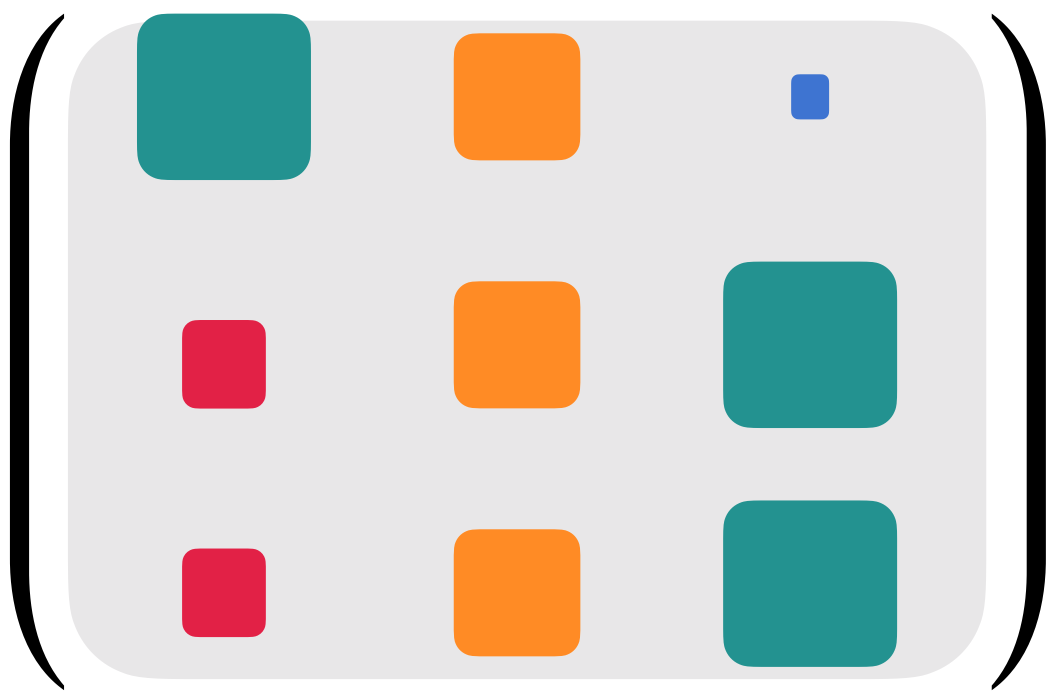

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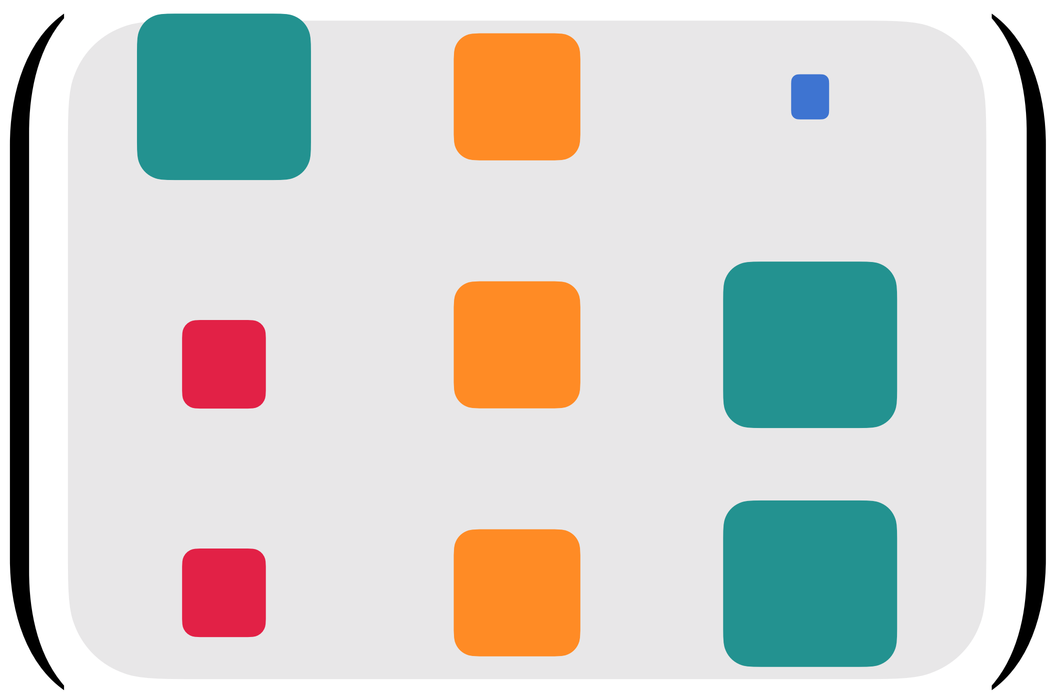

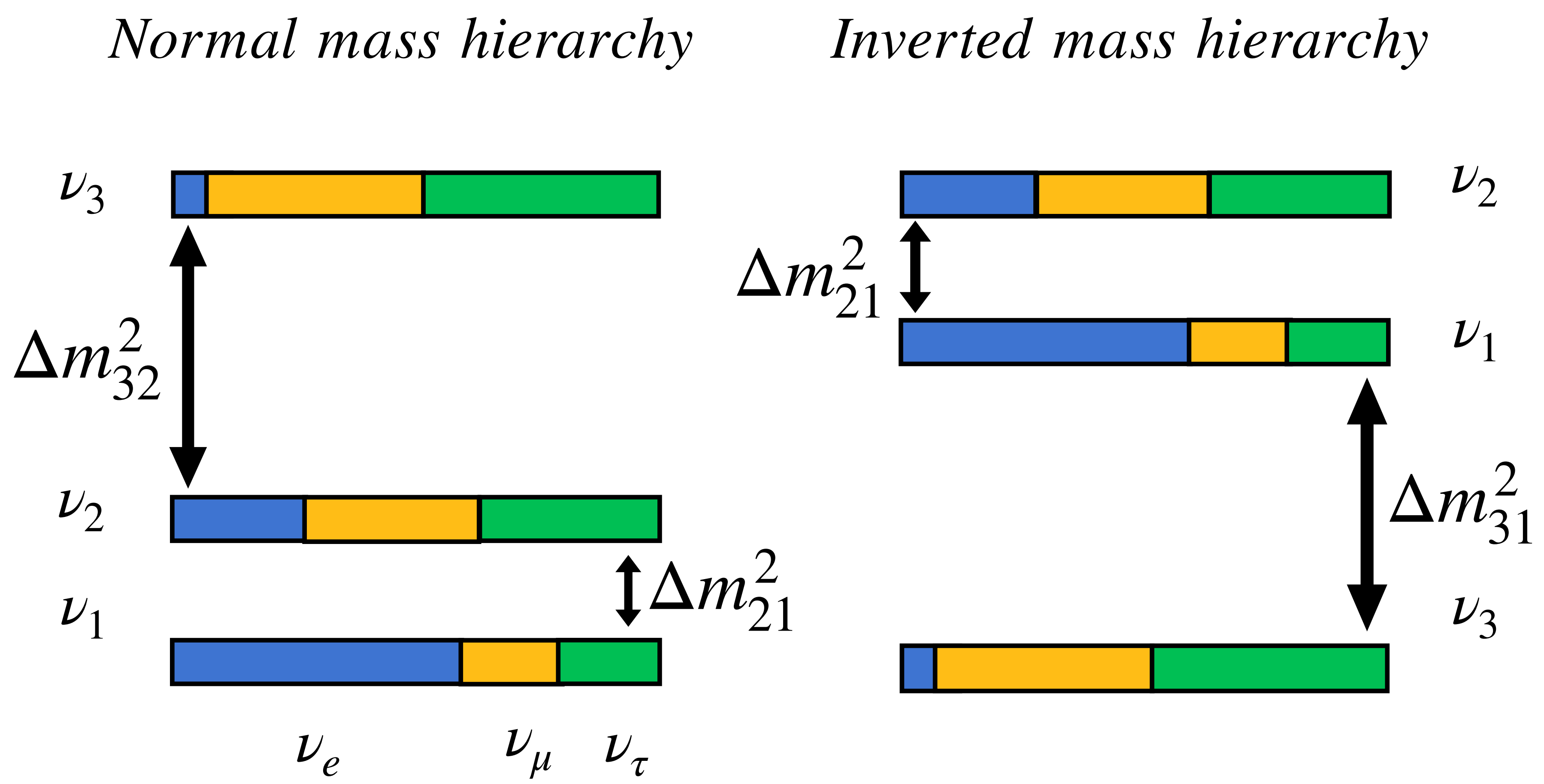

Mass ordering

Neutrino Oscillation Measurements

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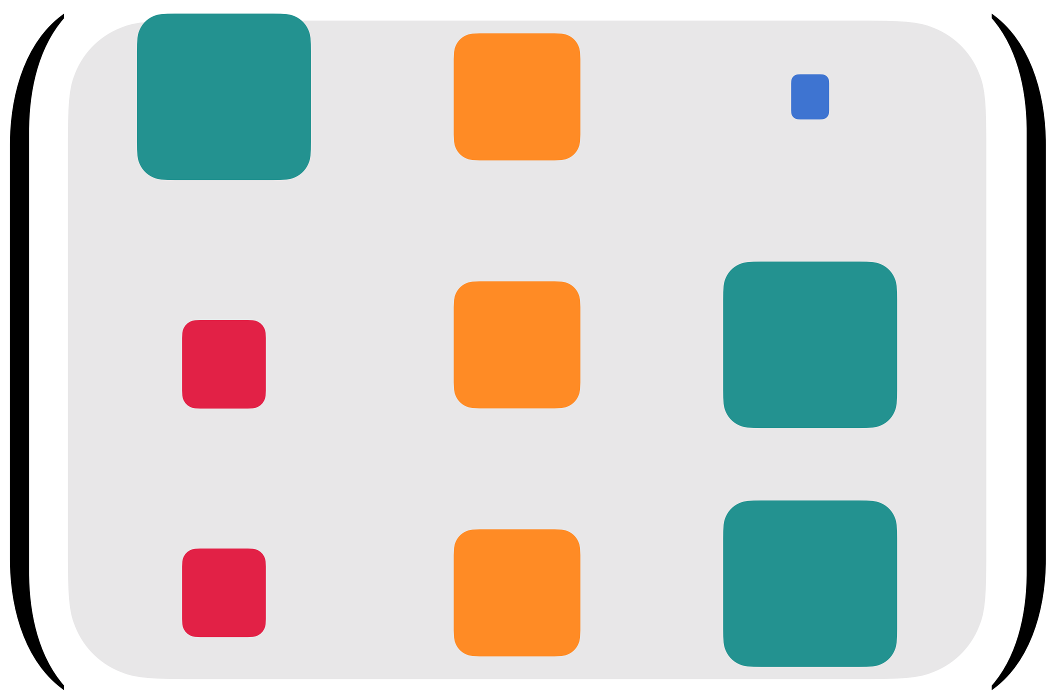
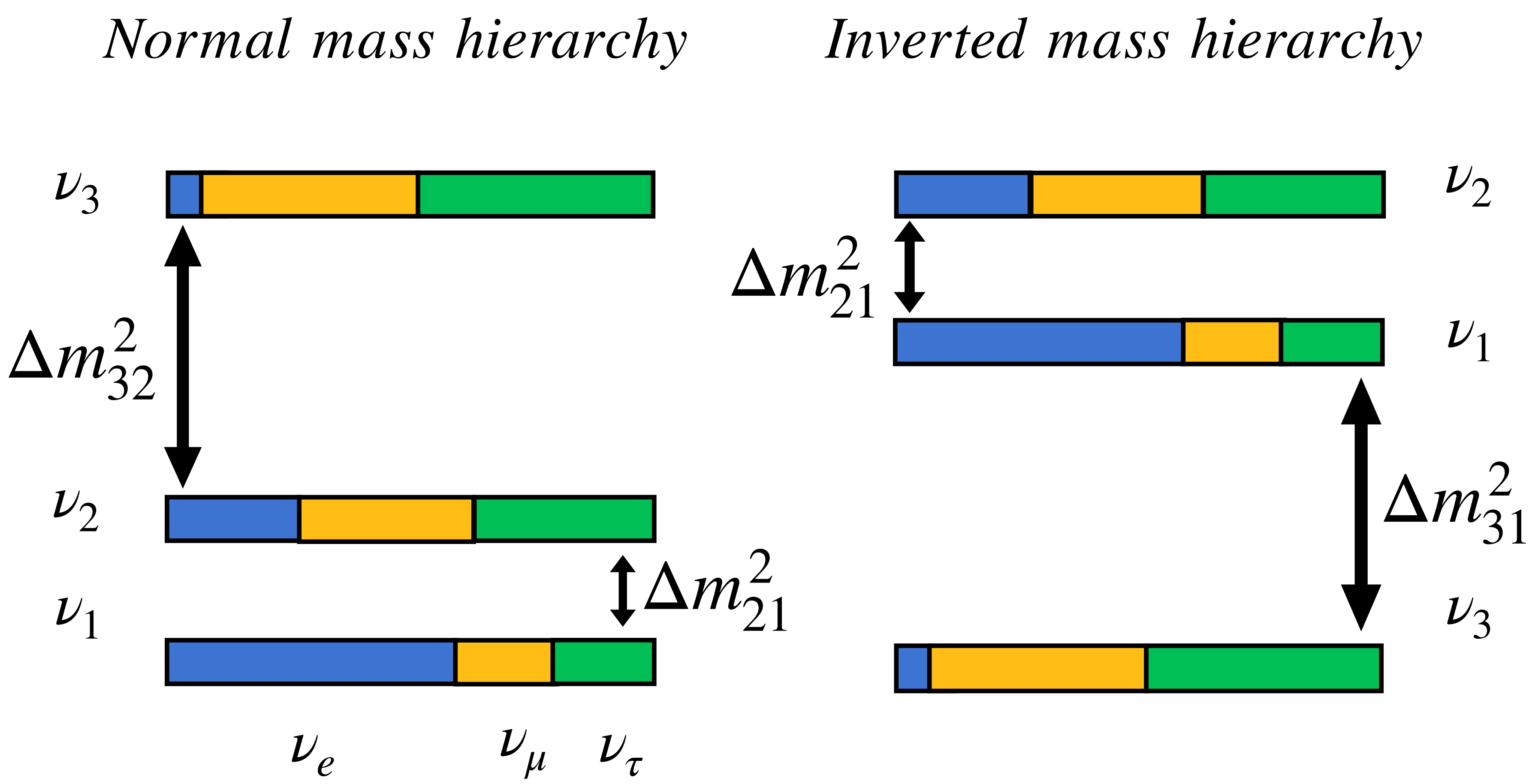
δ_{CP}

Hyper-Kamiokande





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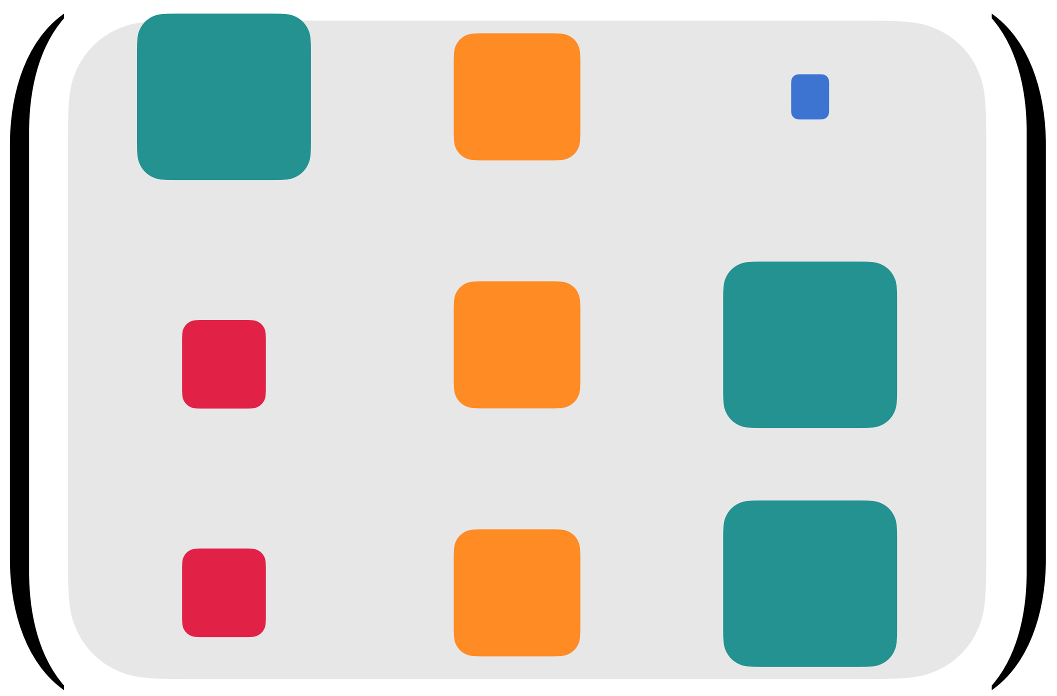

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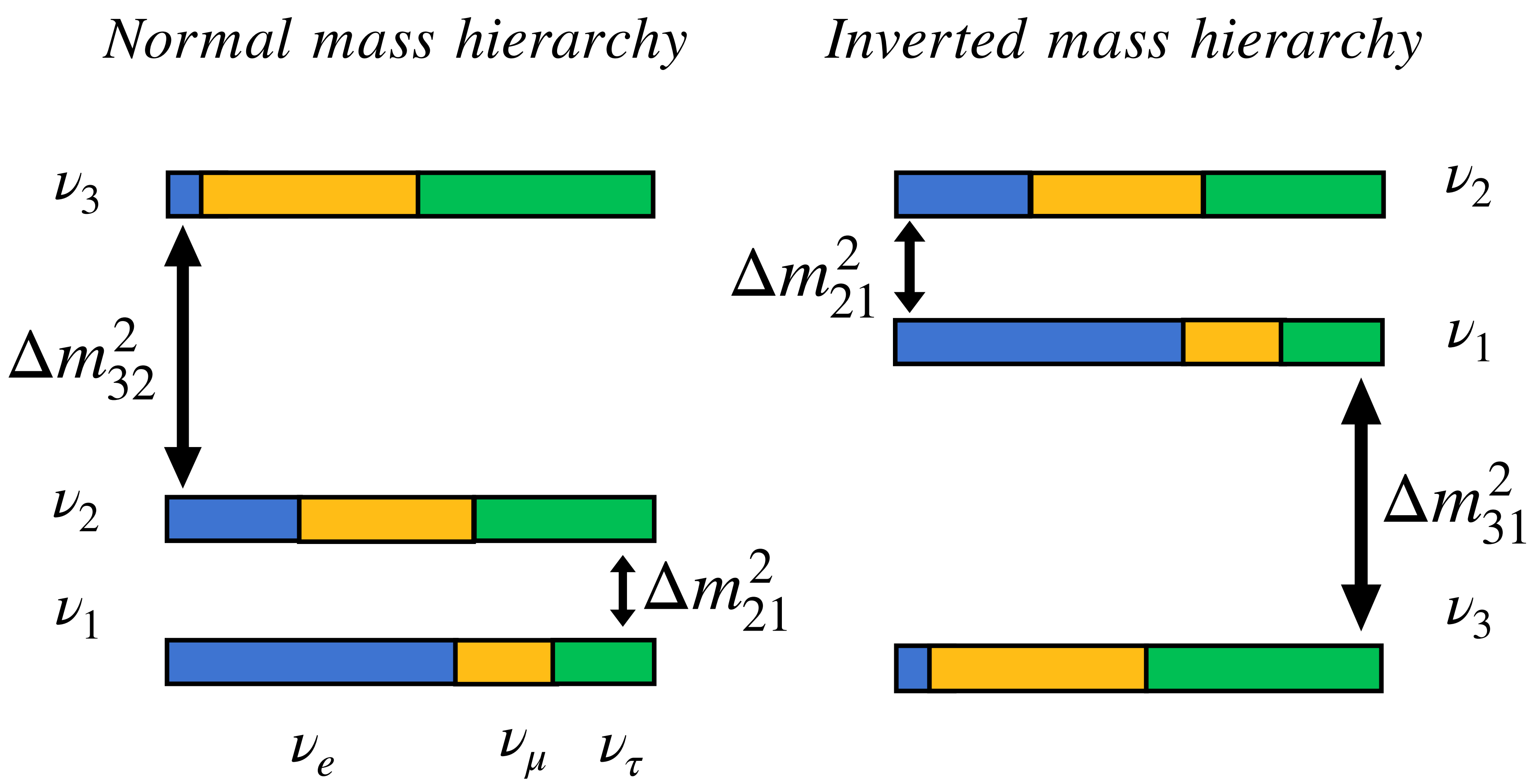

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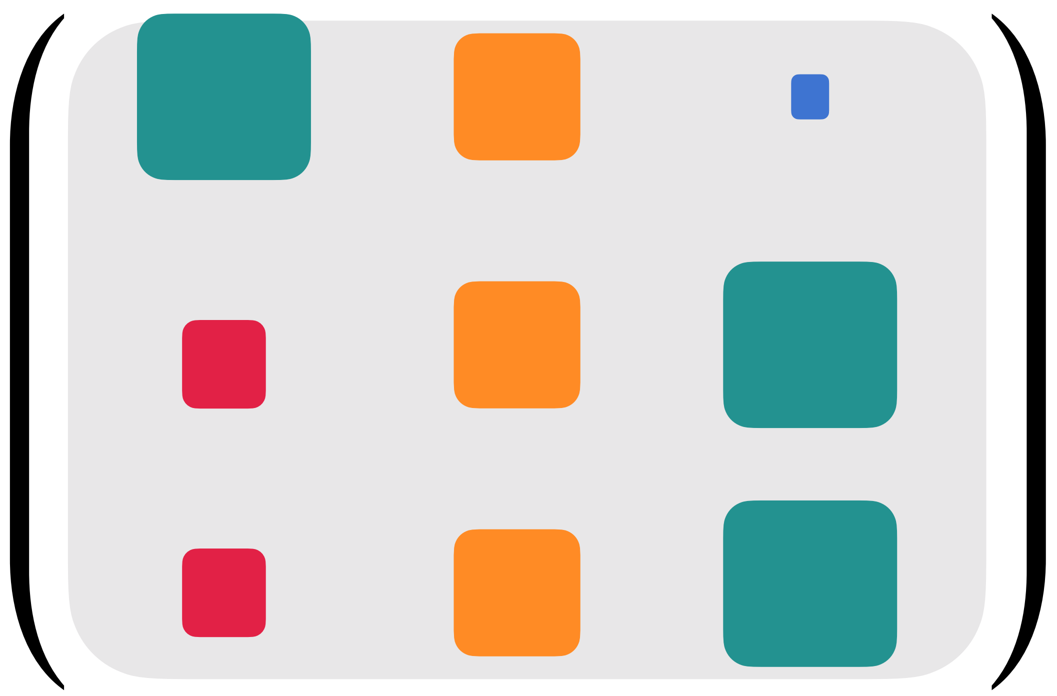

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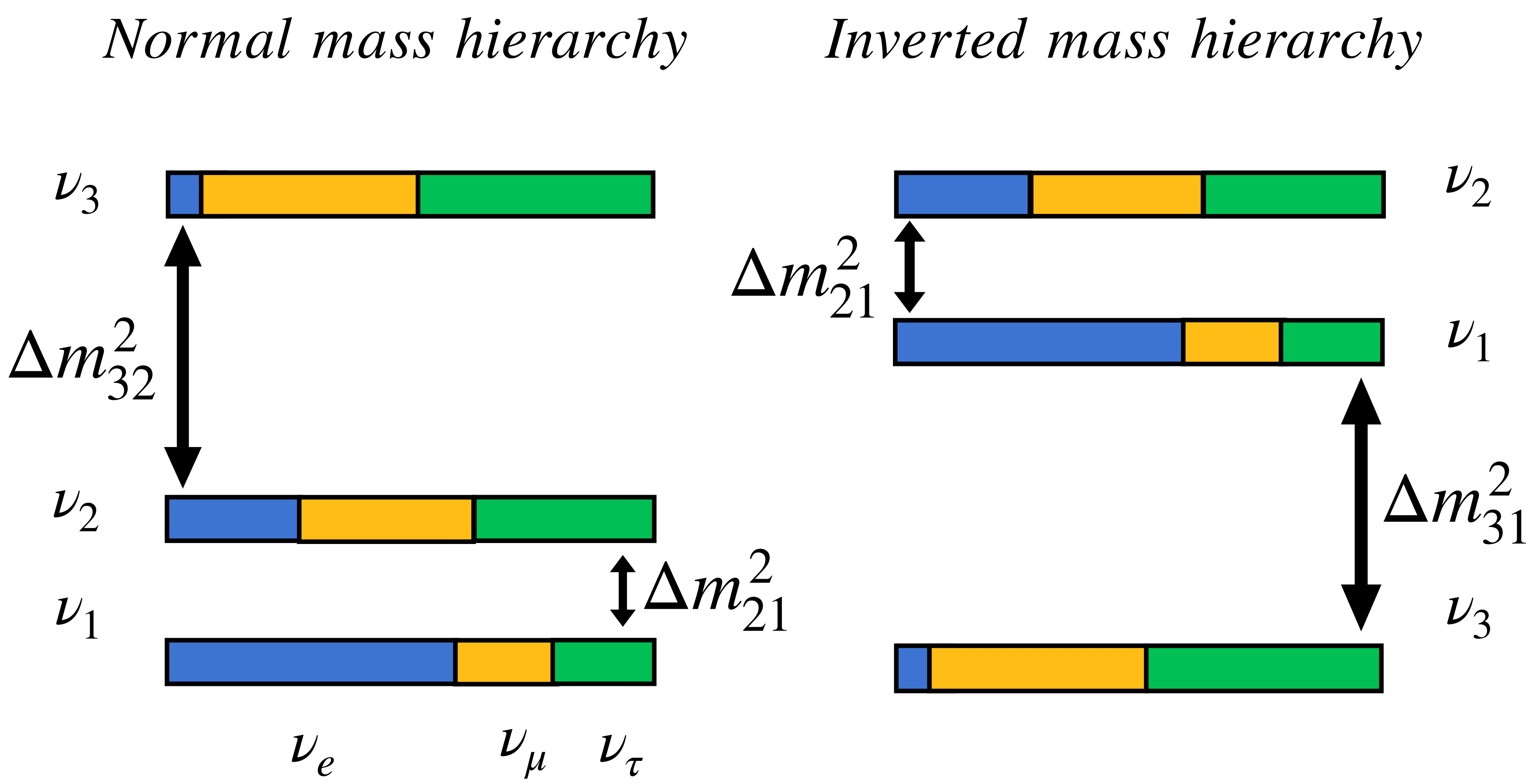

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JUNO

DUNE

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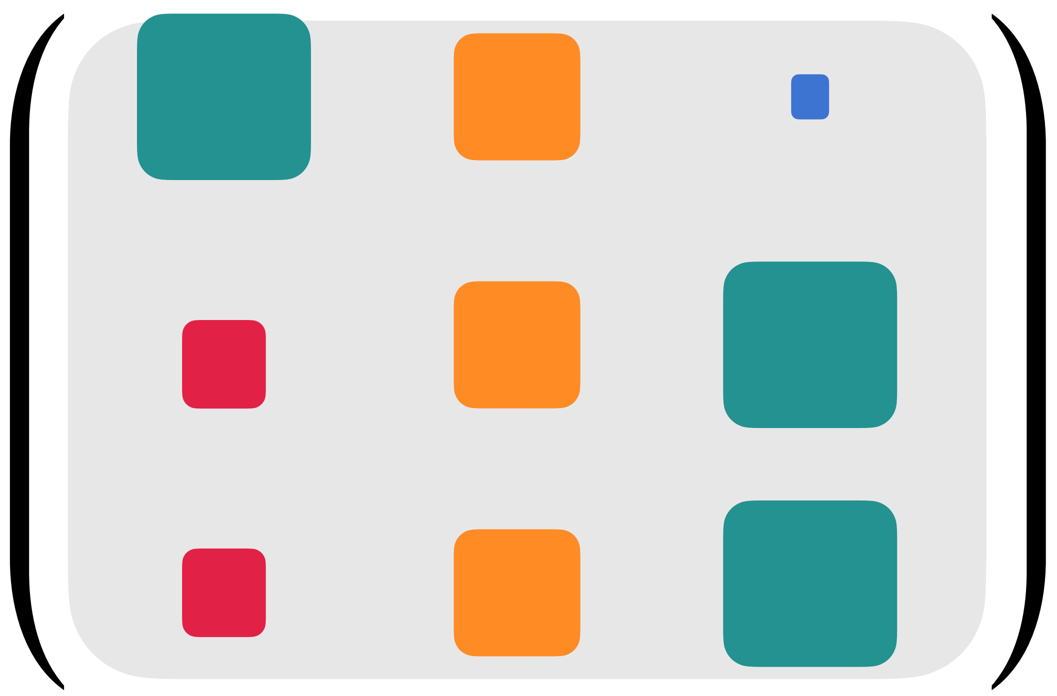

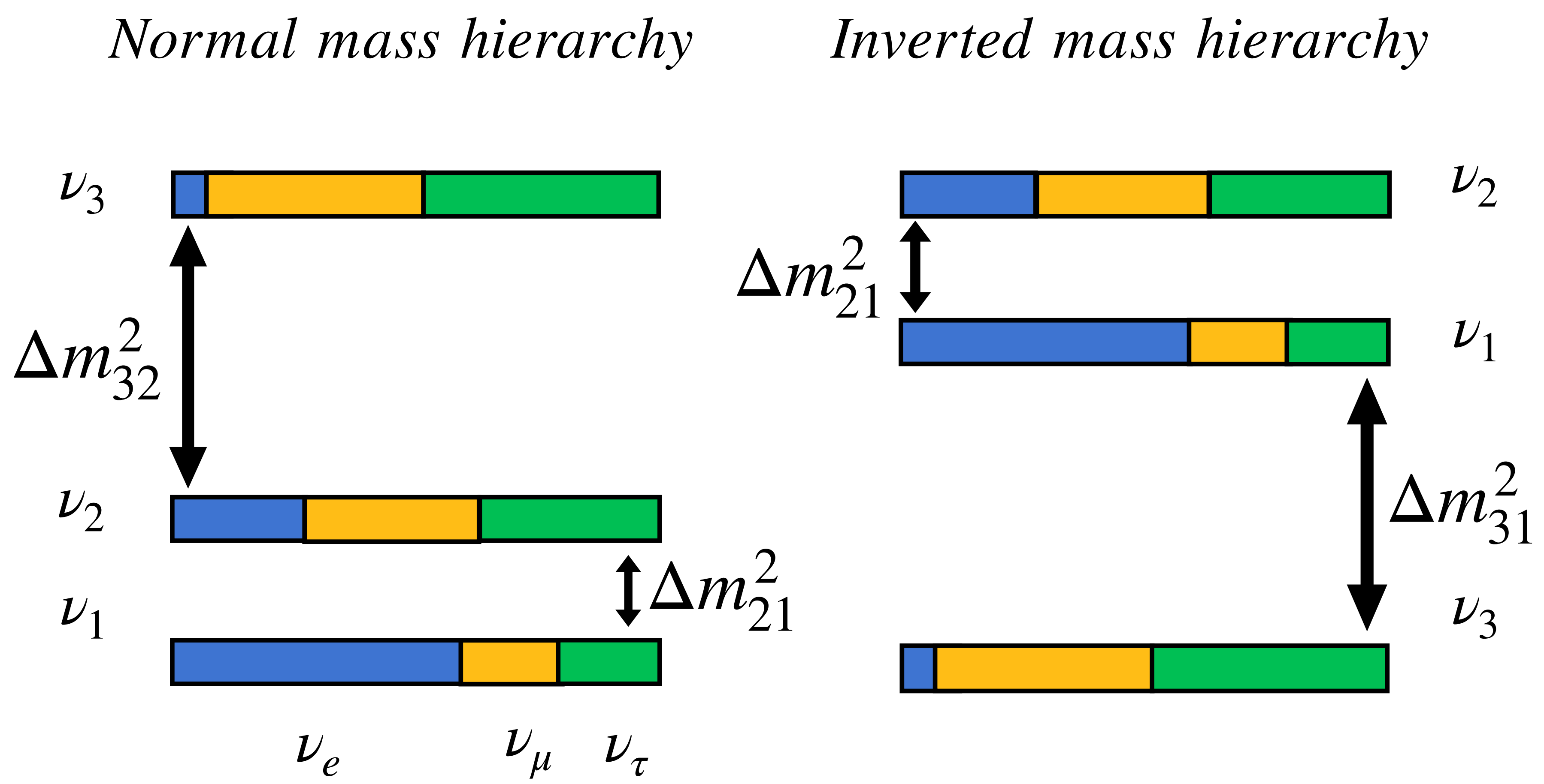

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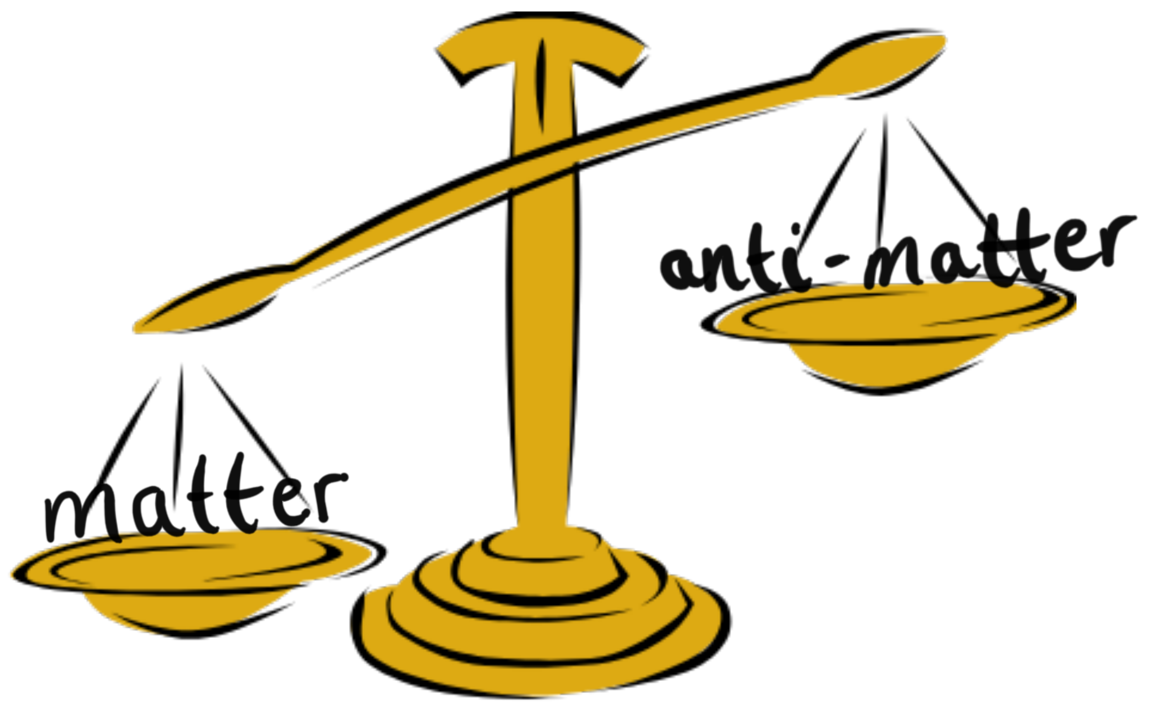

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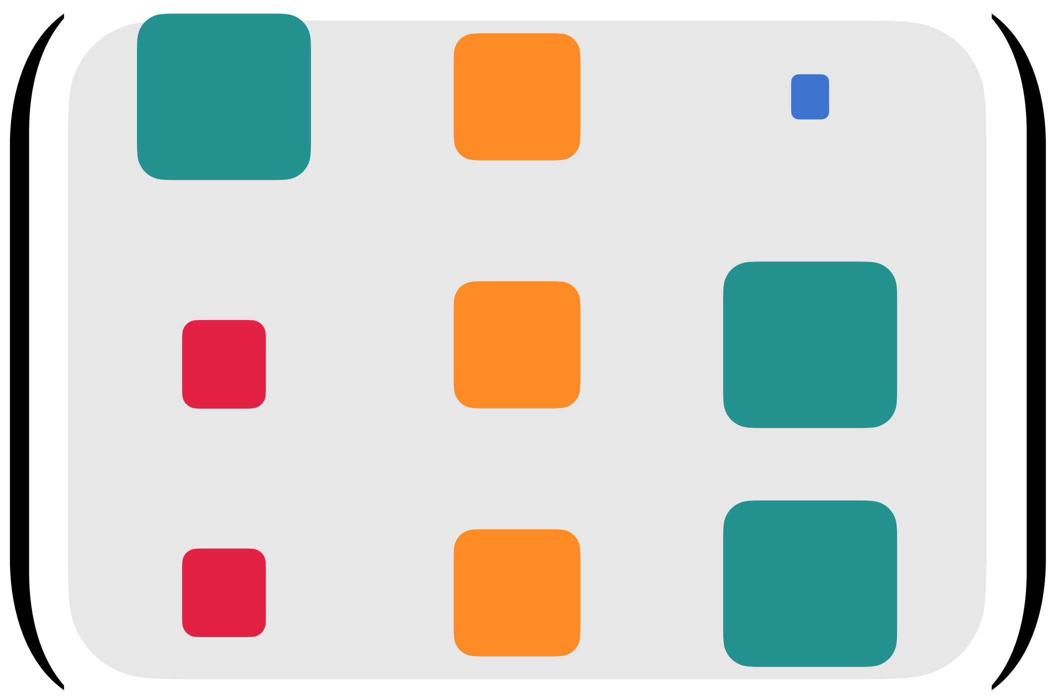

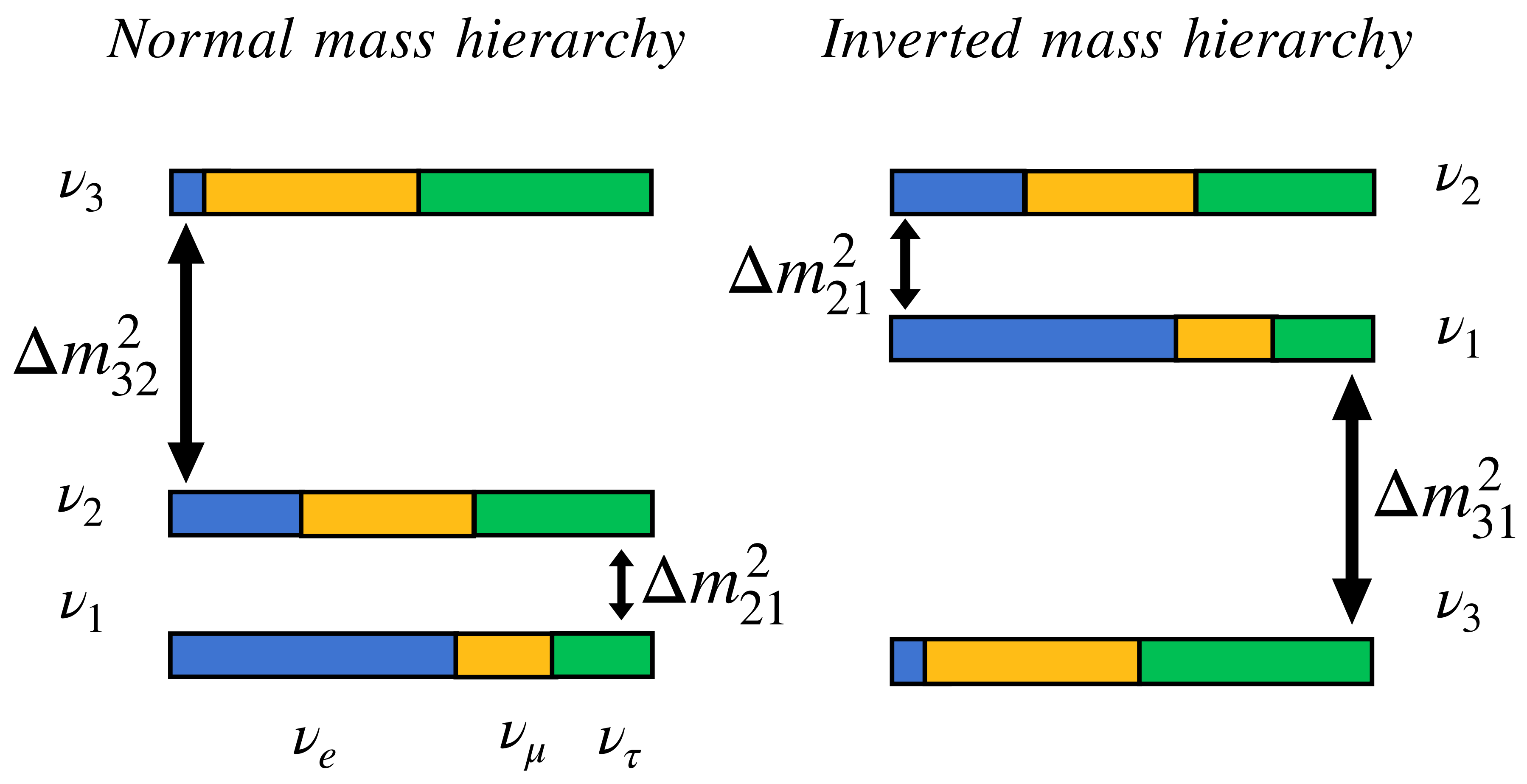

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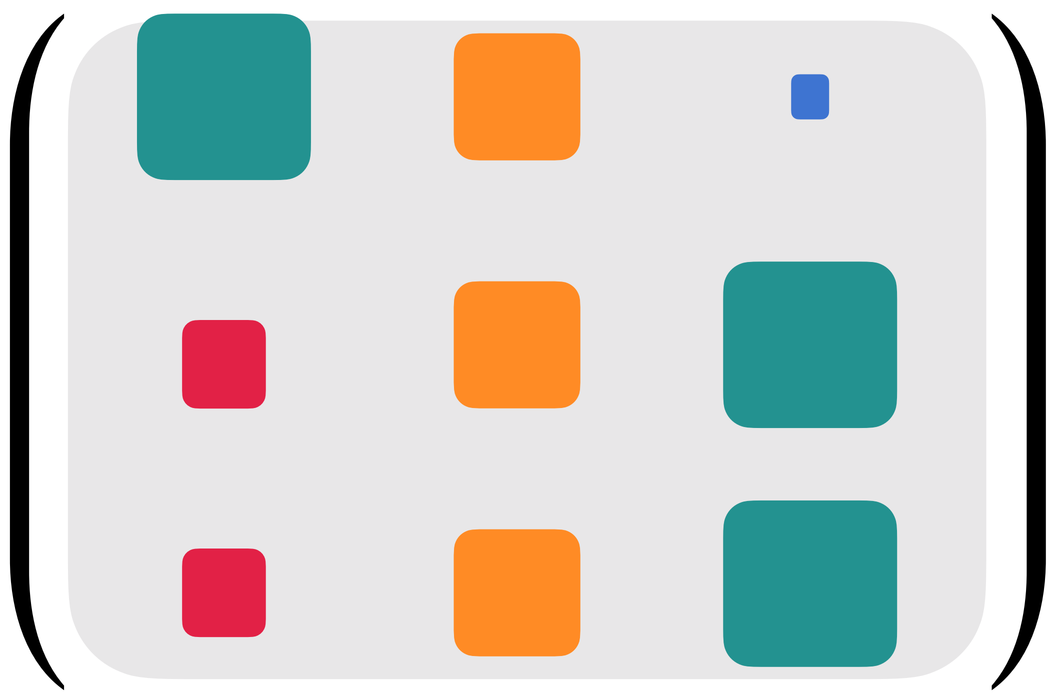

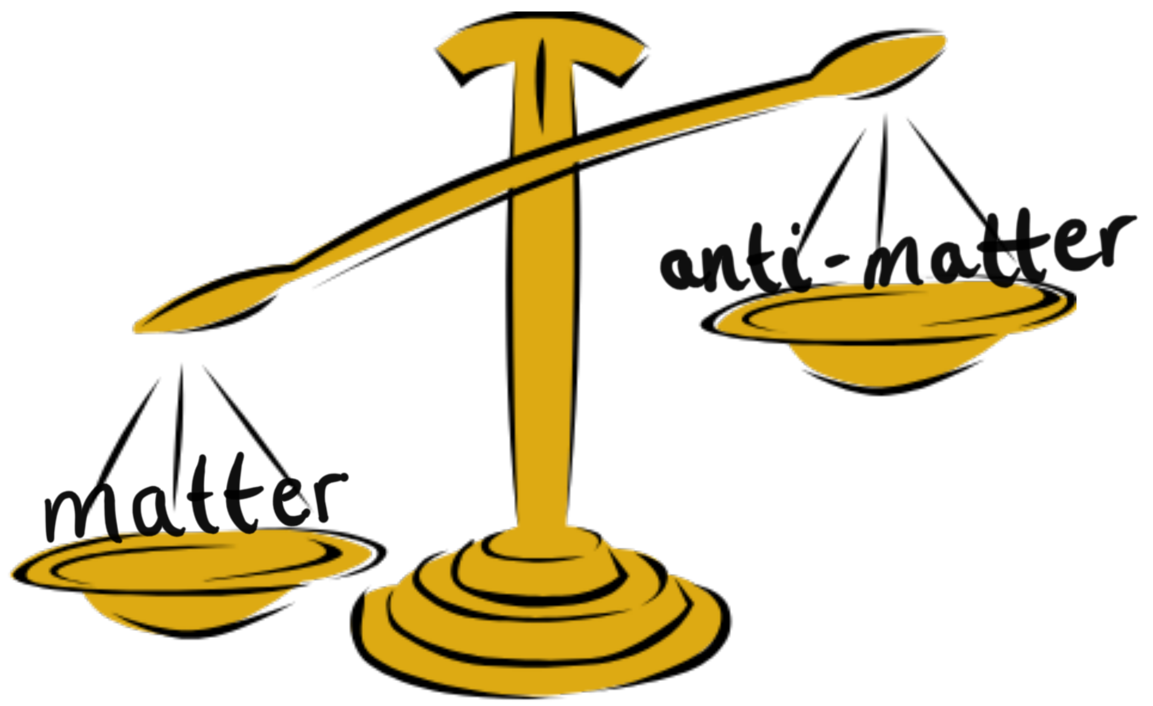

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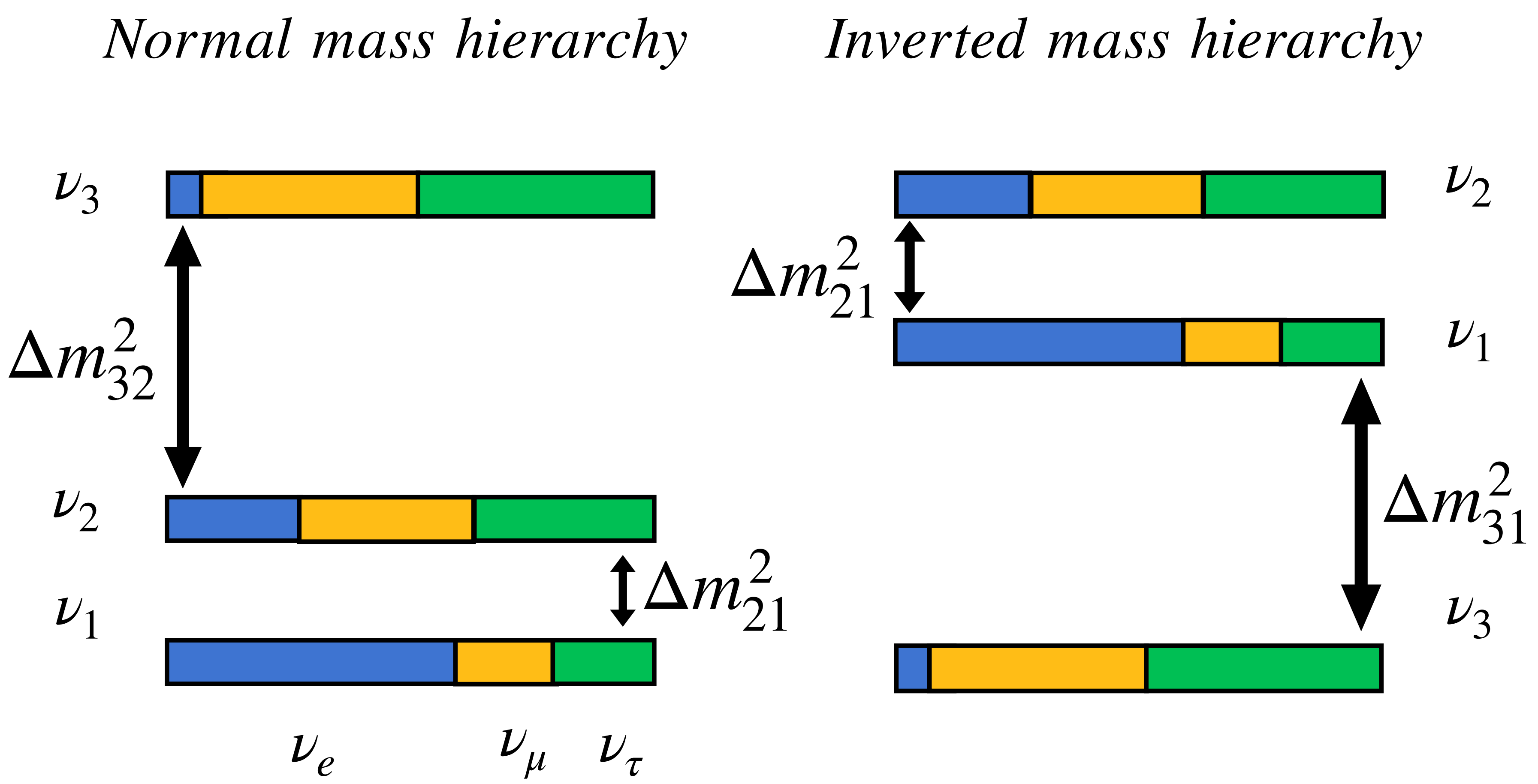
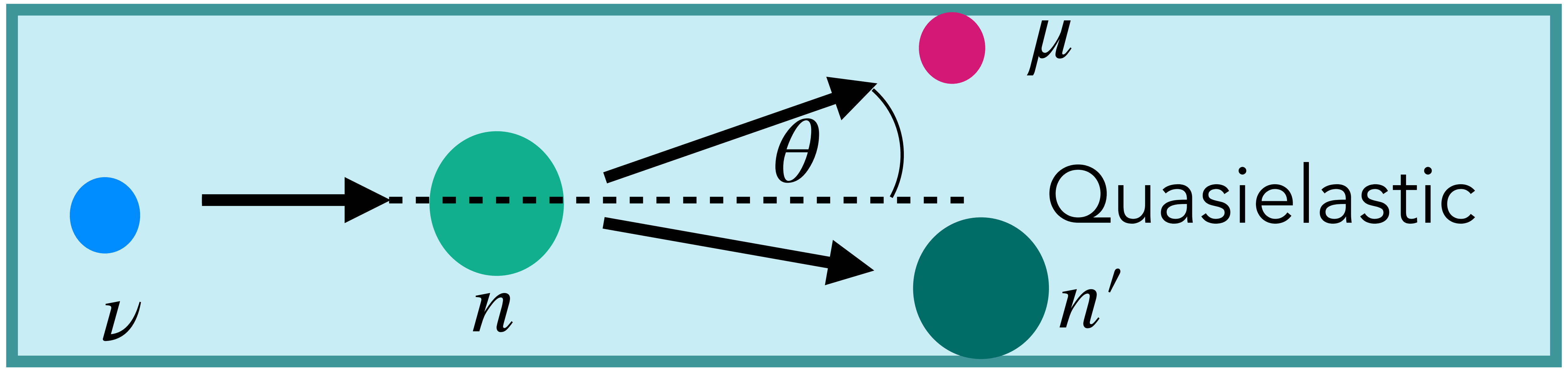
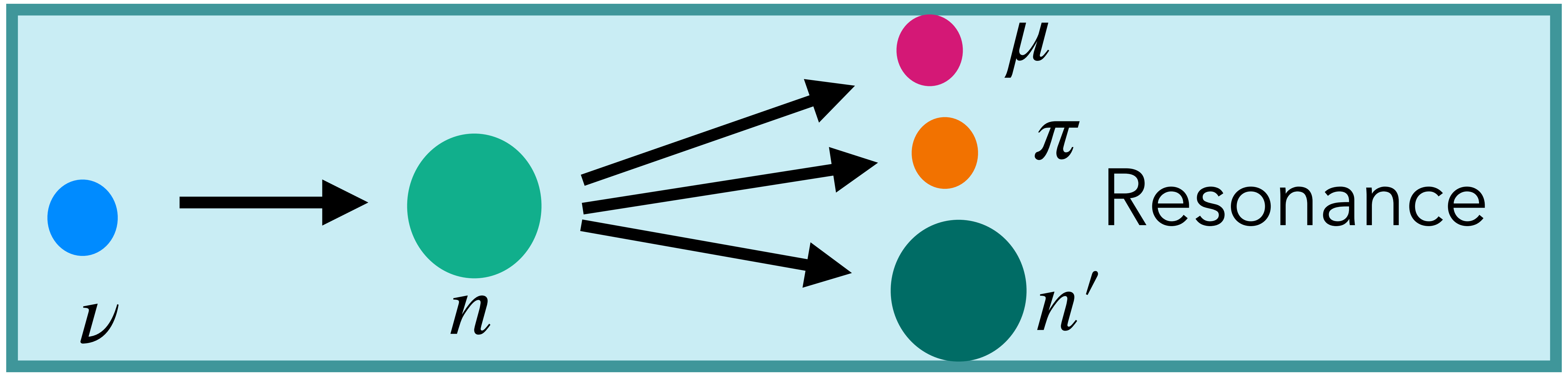


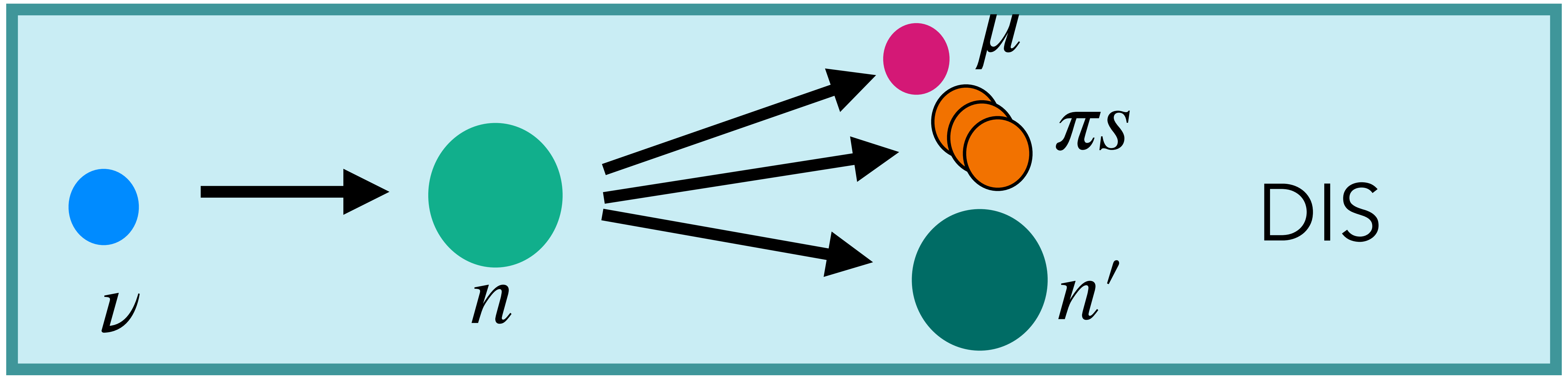
Mass ordering

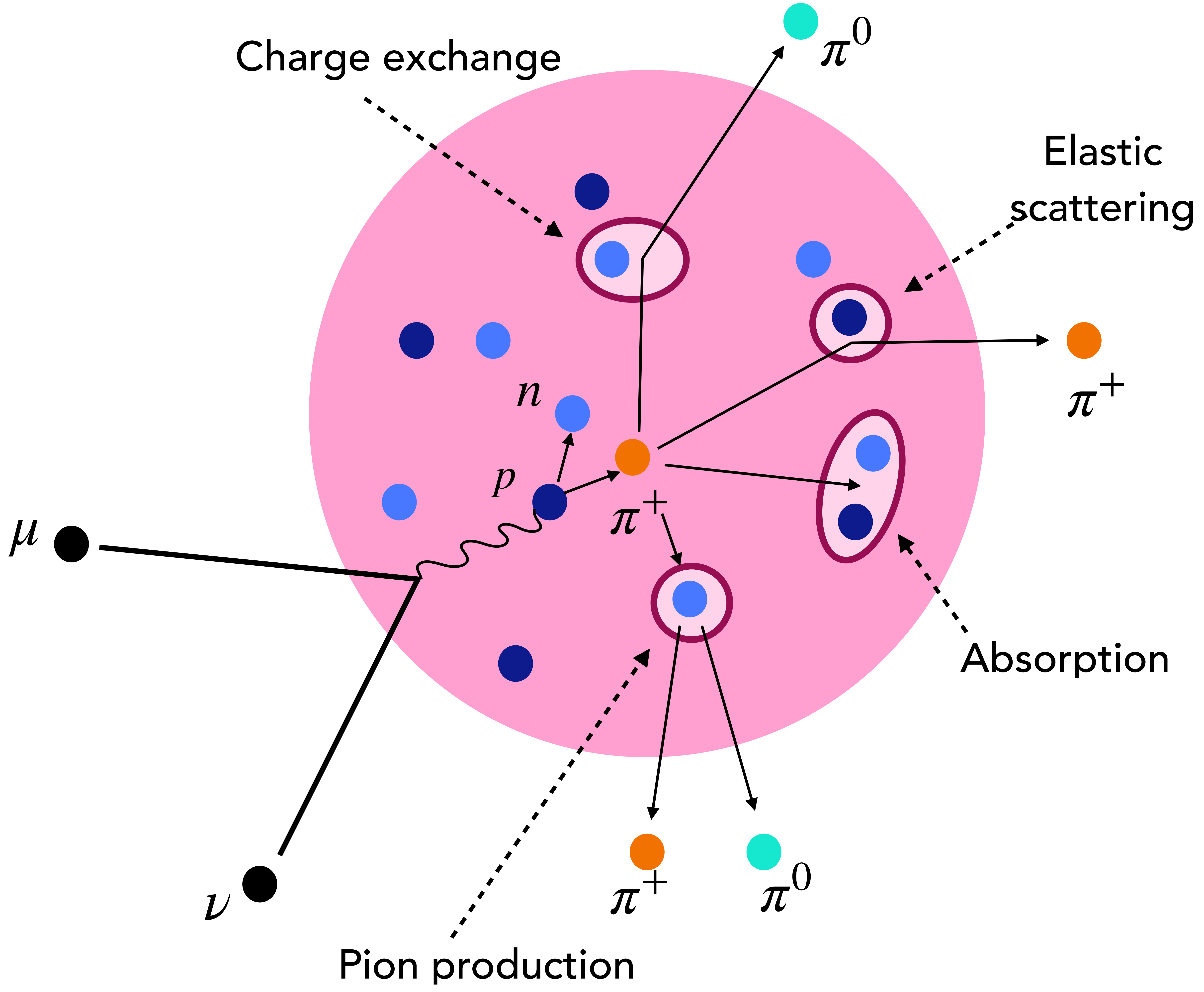
- Will see a large flux of neutrinos from beam at Fermilab, and atmospheric neutrinos.
- **No detection of neutral particles.**

Neutrino-nucleus interactions





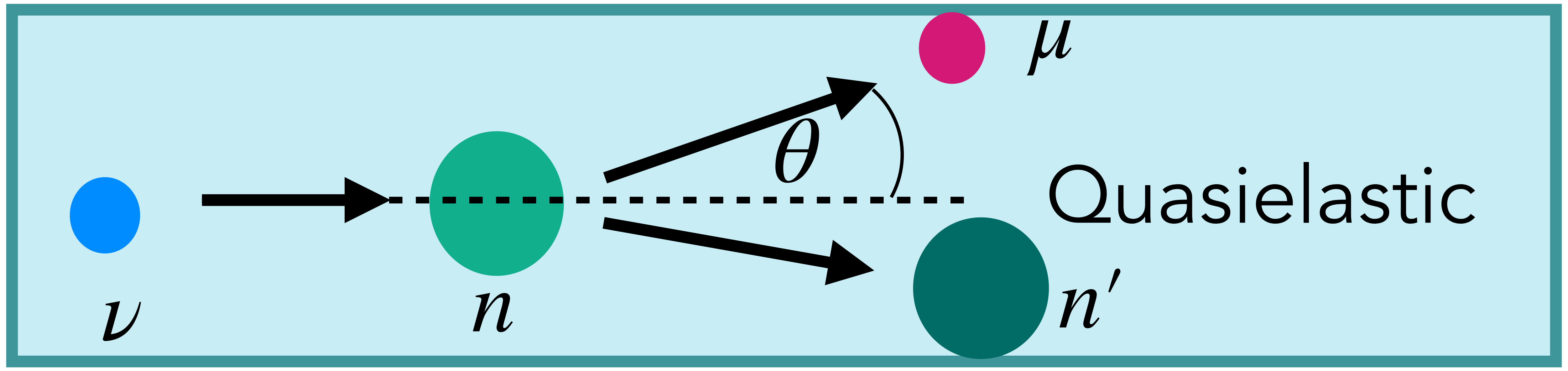




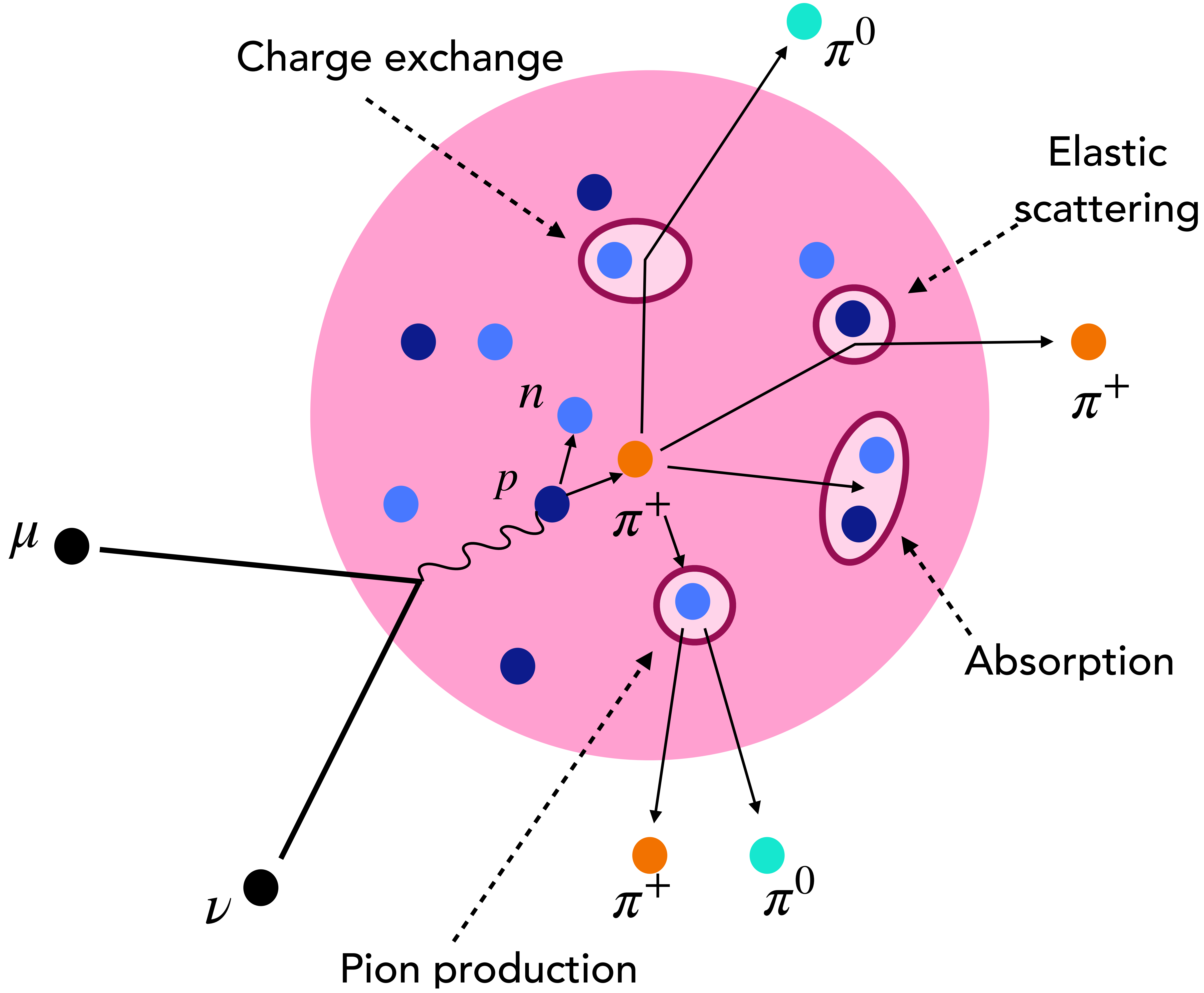
$$E_\nu = ?$$

Slide from L. Cremonesi\T. Golan

Neutrino-nucleus interactions



$$E_\nu = \frac{2M_n E_\mu - M_n^2 + M_\mu^2 - M_p^2}{2(M_n - E_\mu + \sqrt{E_\mu^2 - M_\mu^2}\cos\theta}$$



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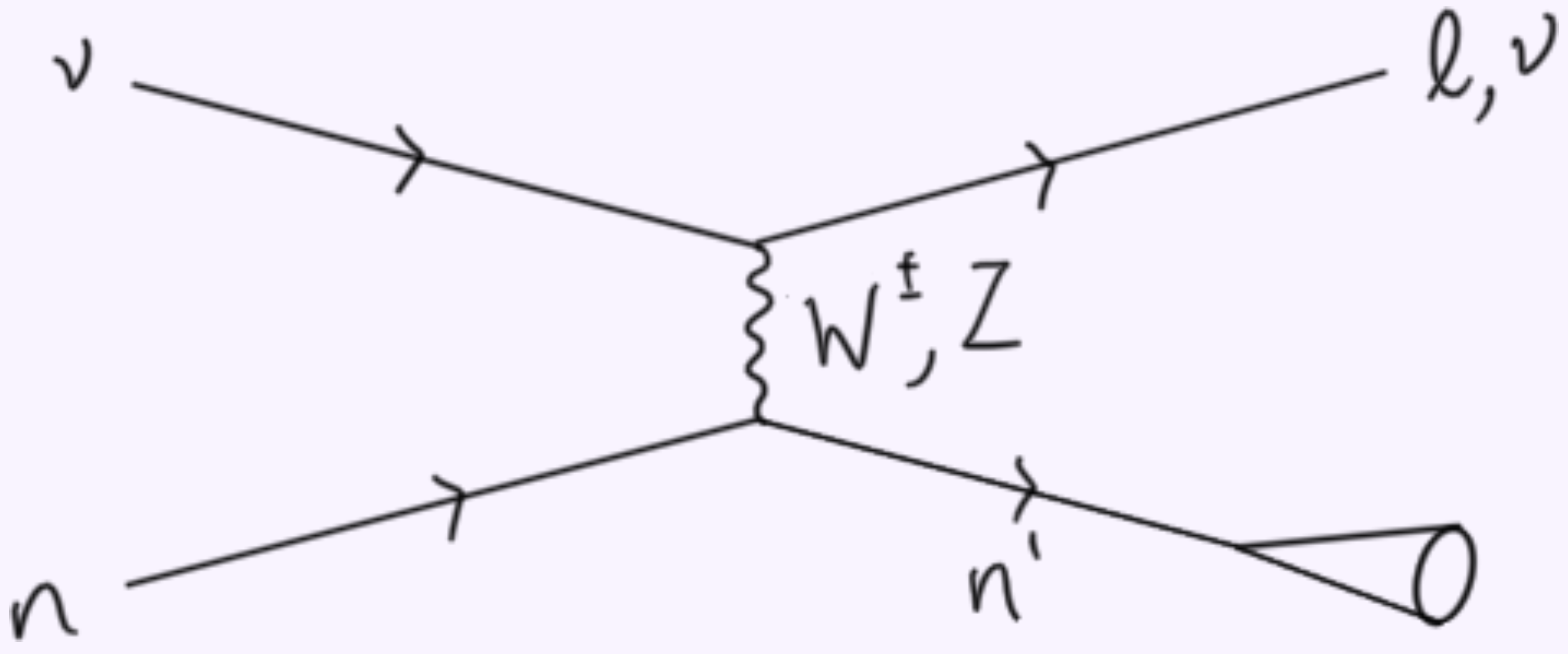
Dataset and Network



Generate 5×10^5 $\nu_\alpha(\overline{\nu_\alpha})$ events with energies from 0.2 - 6 GeV using NuWro.

Use DUNE flux for beam neutrinos, flat flux for atmospherics.

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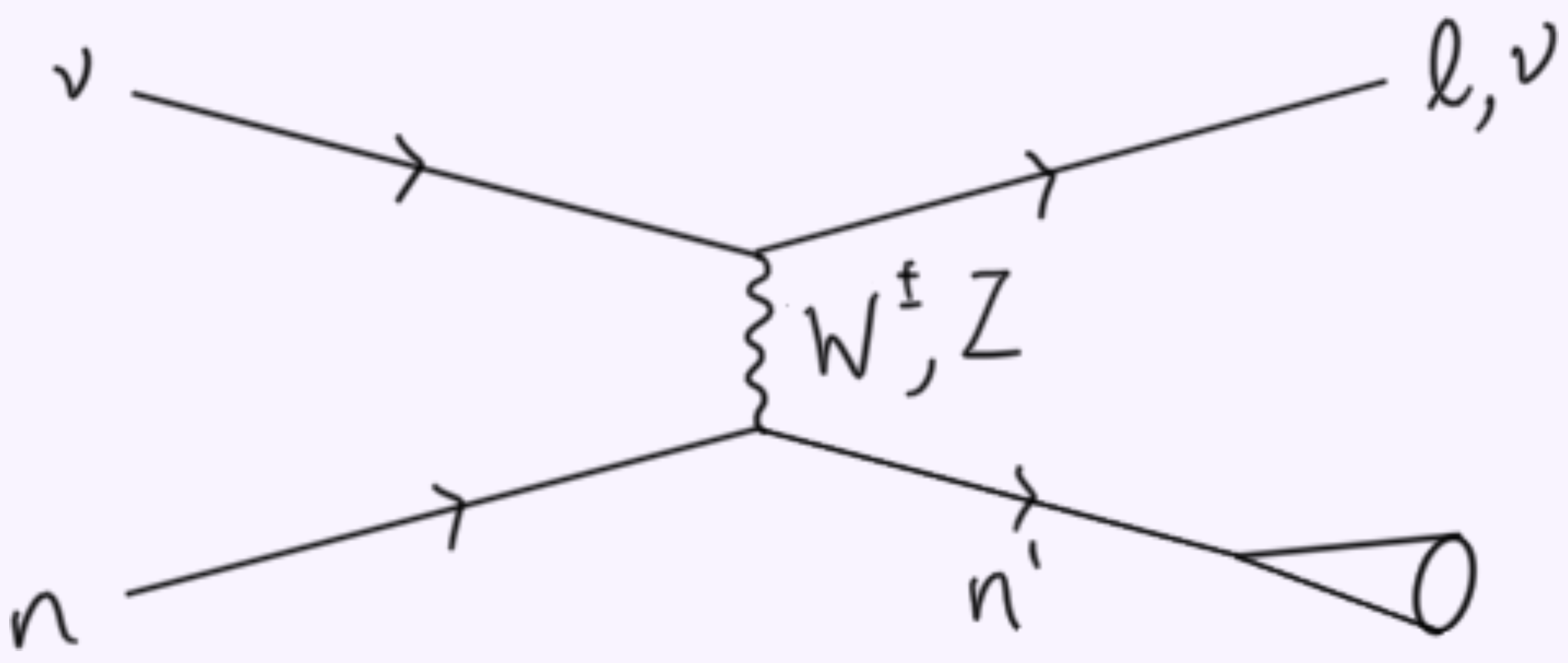

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Randomly rotate events if training for atmospherics.

Remove* invisible (long lived & neutral) particles.

Combine all particles of the same type into single entity.

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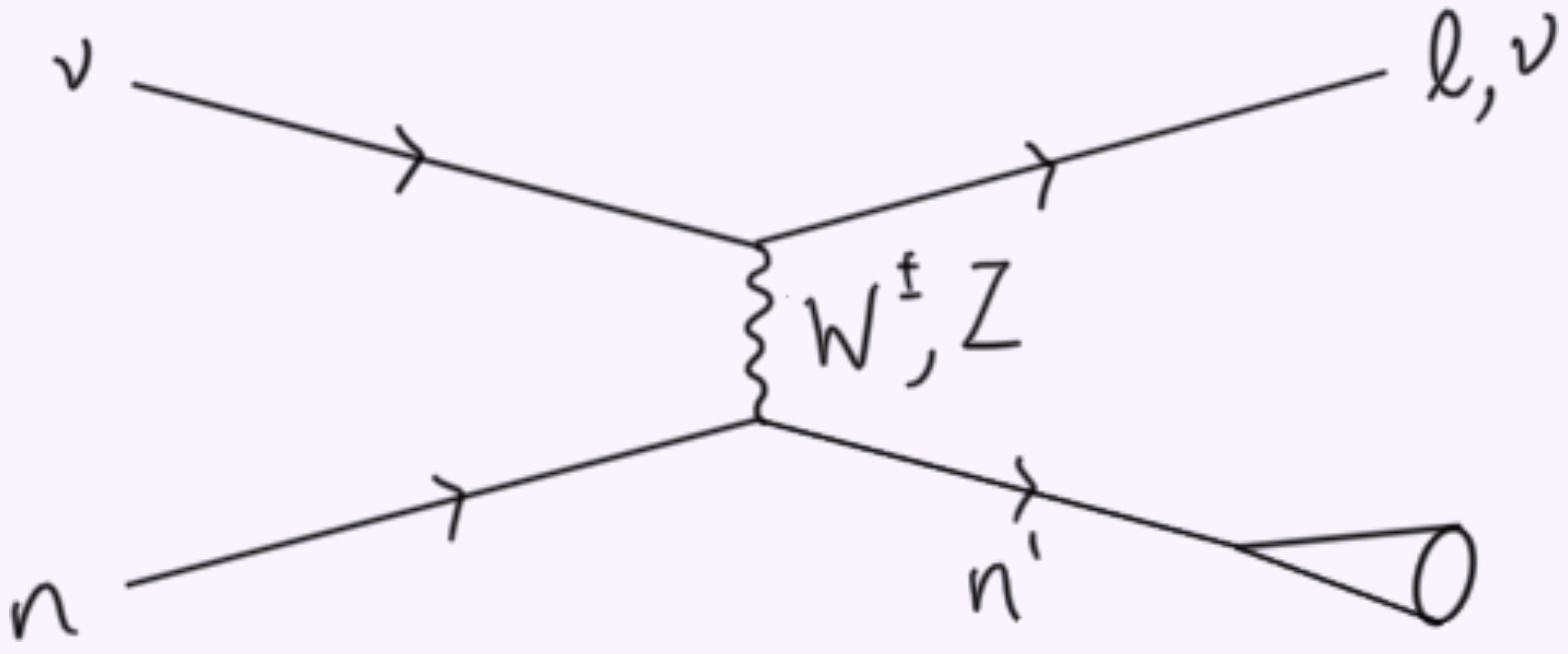

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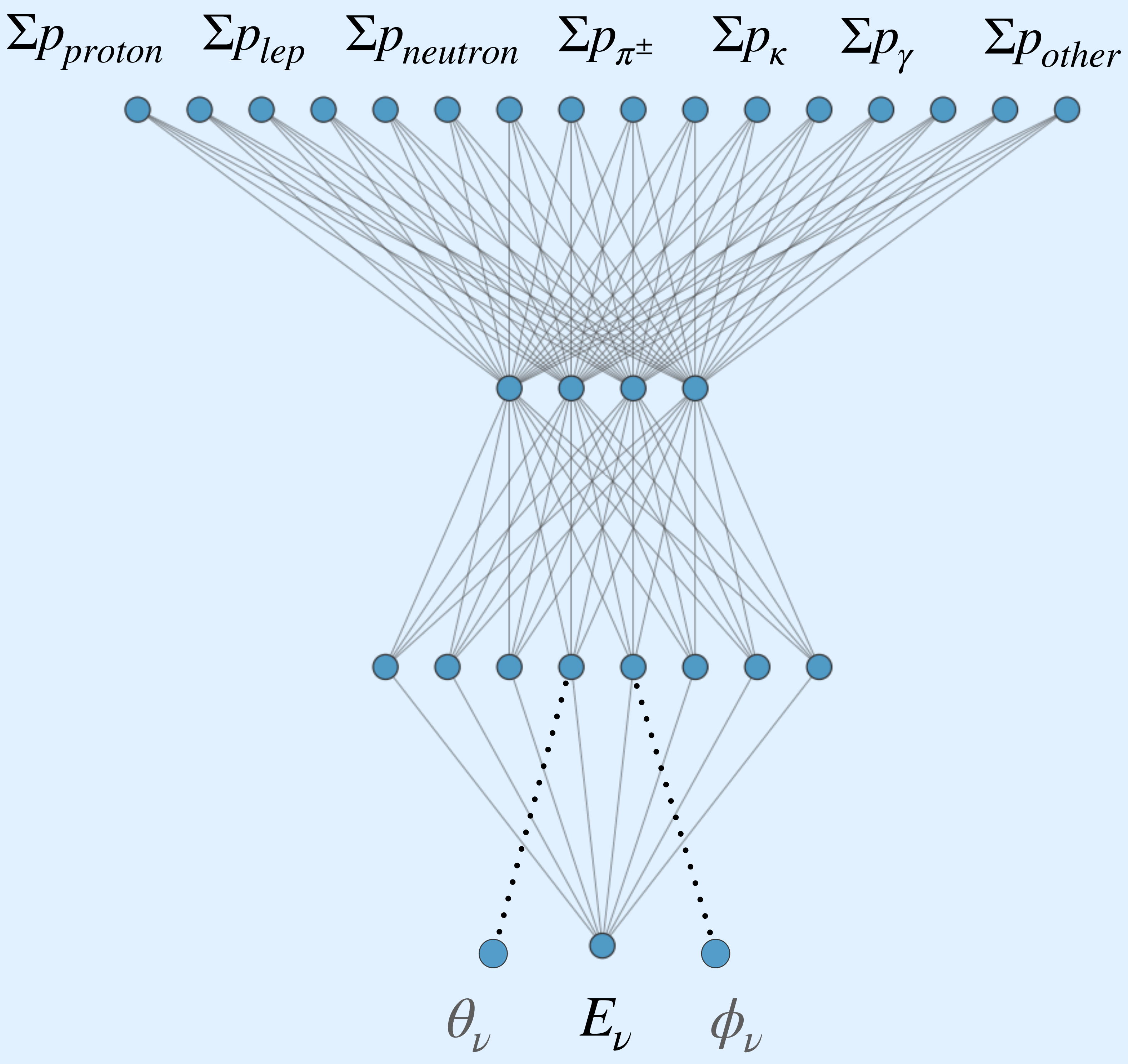
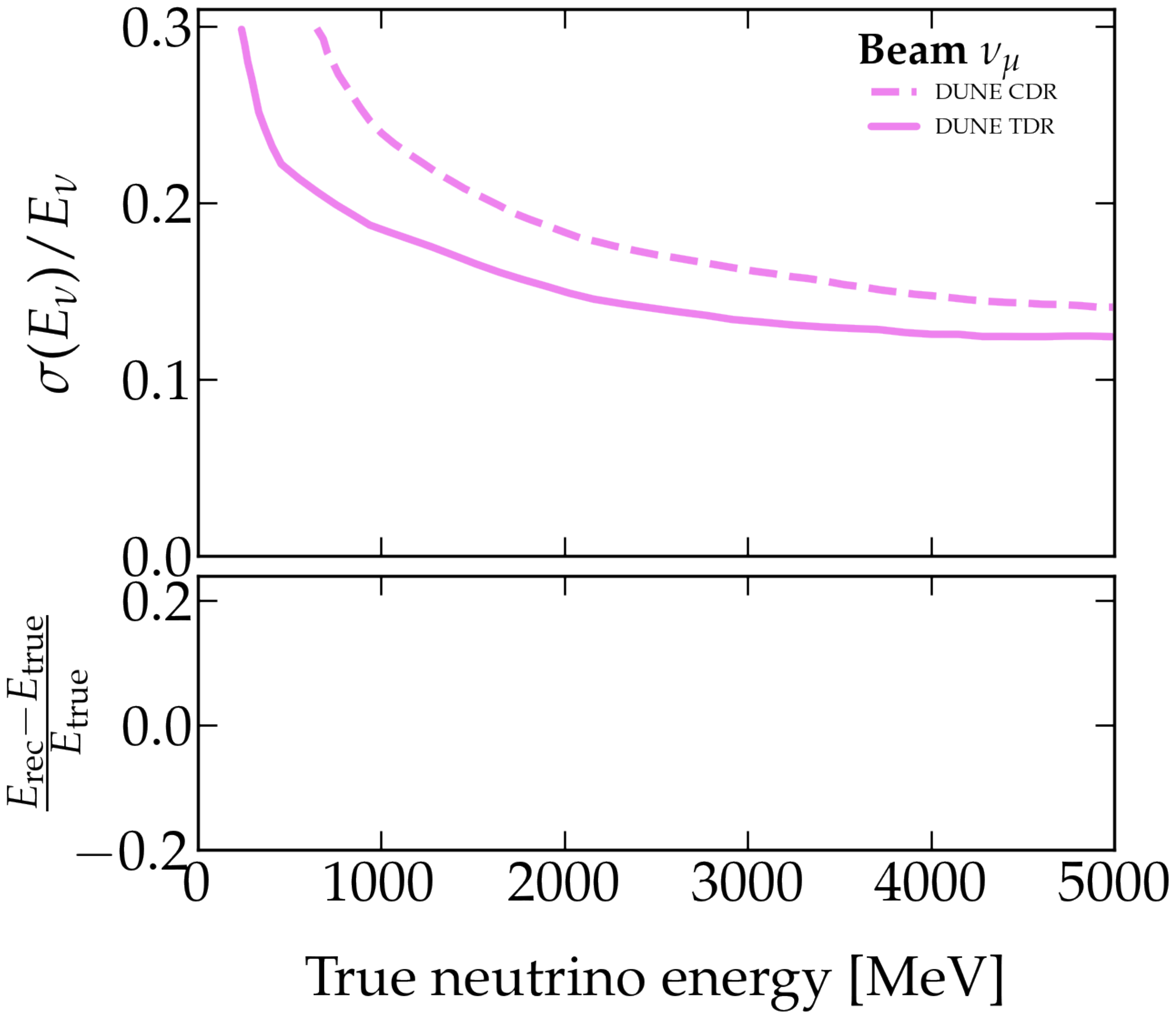


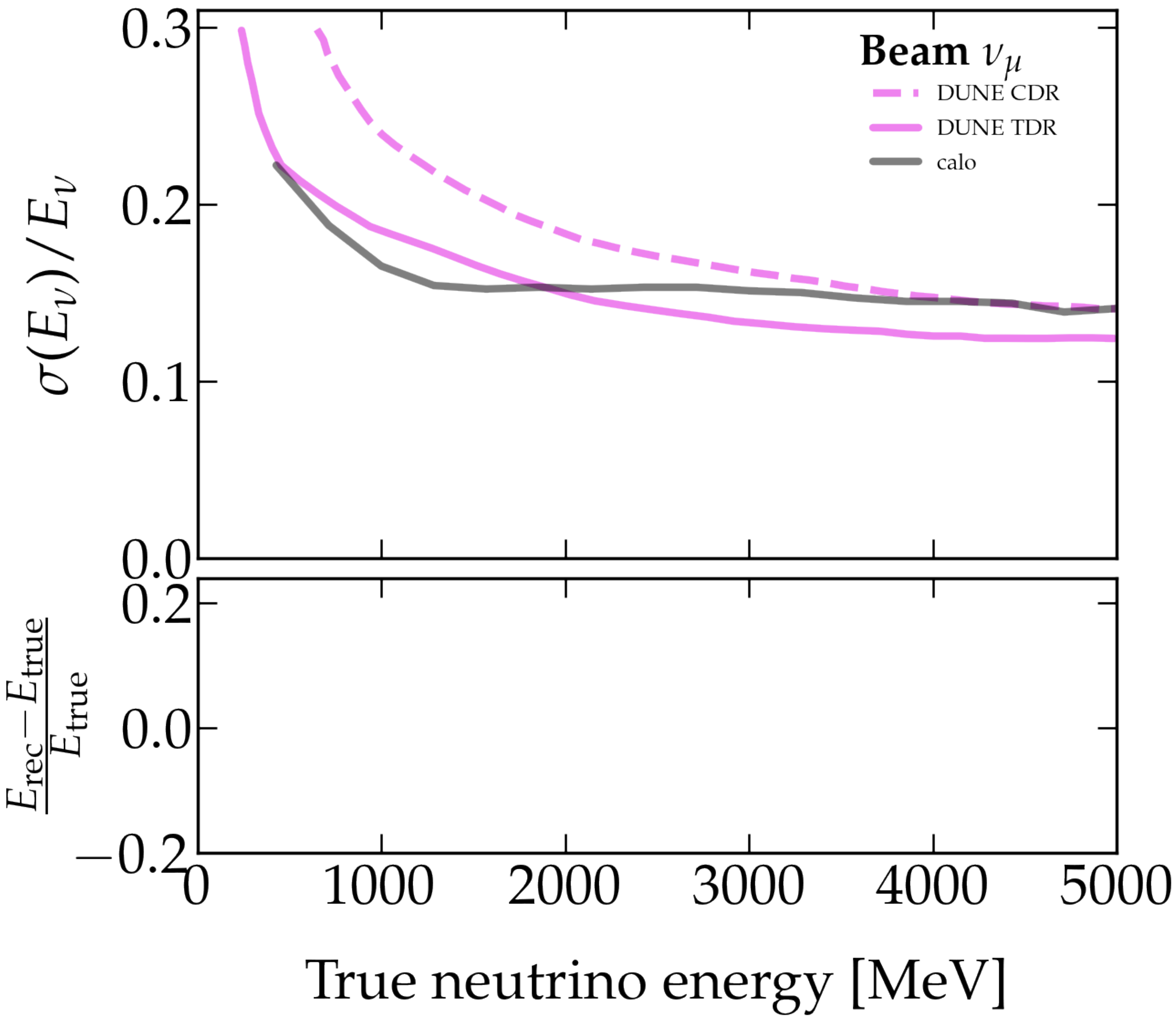
Feed vector sum of particle-groups 4 momenta to fully connected layer regression network

Results - Beam



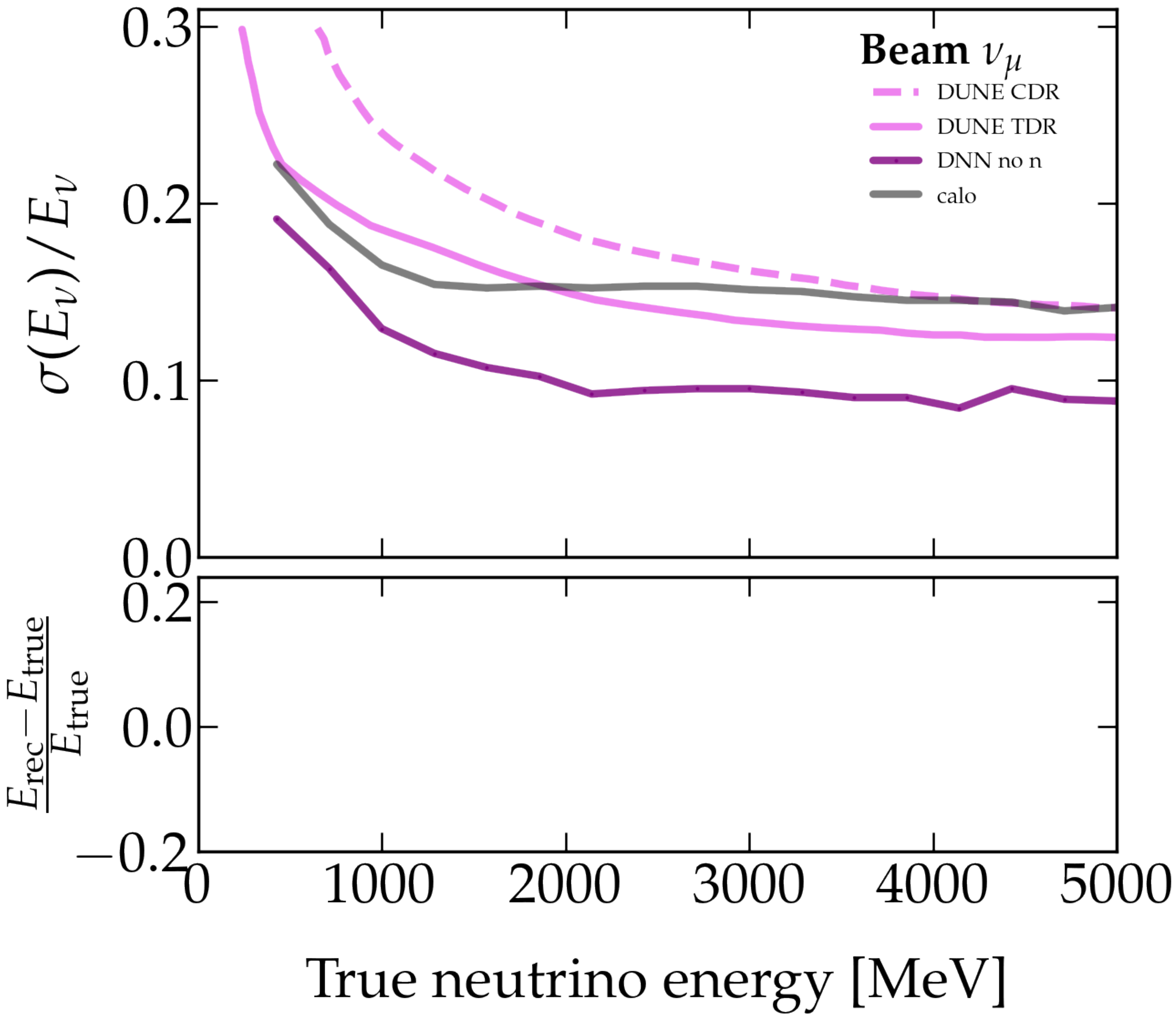
- Best resolution from DUNE Technical Design report is ~13%

Results - Beam



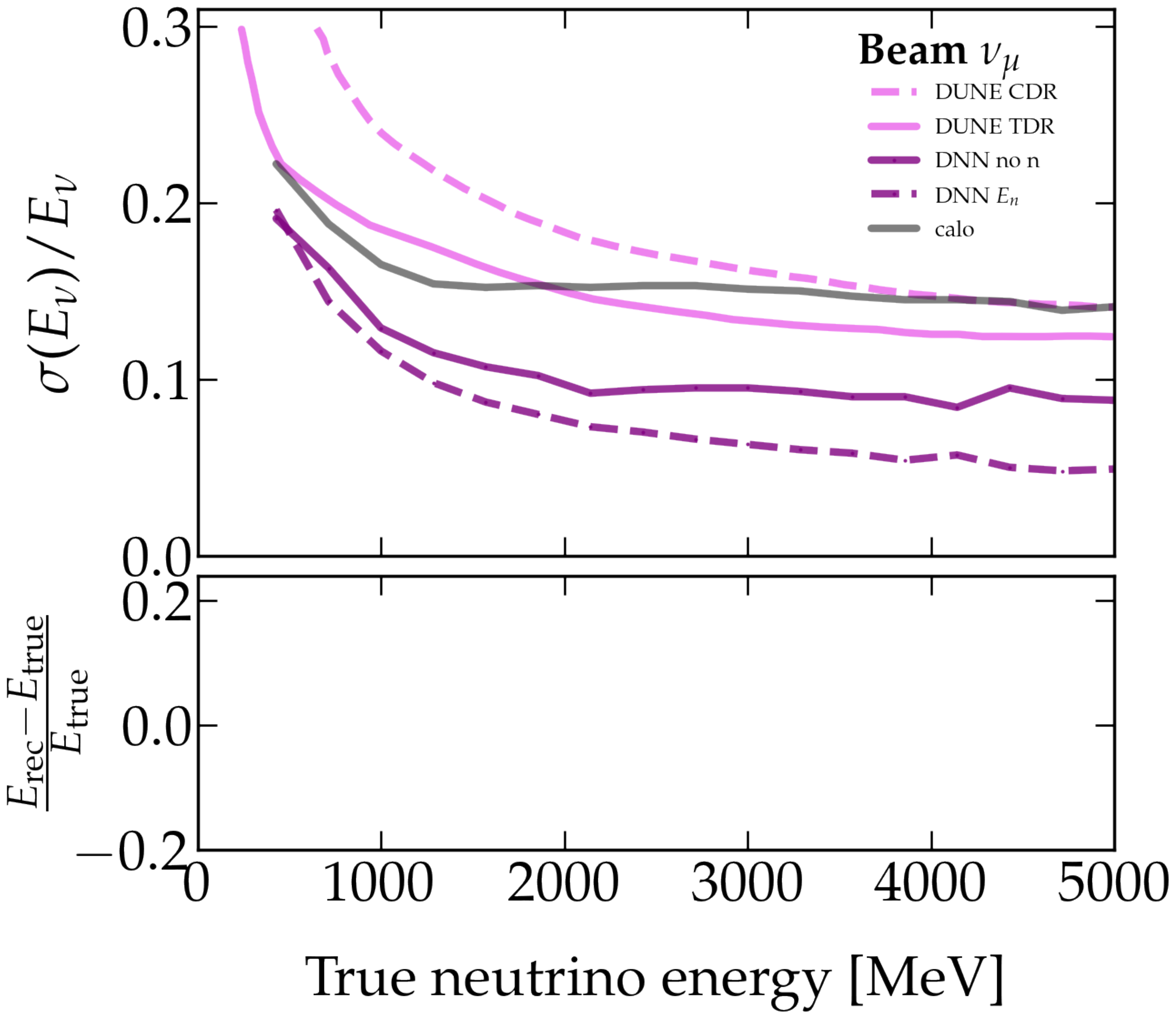
- ‘Calorimetric’ method takes the sum of all visible energy in an event as neutrino energy.
- Approximates design reports reasonably well.

Results - Beam



- DNN applied to events with no neutron information improves on TDR resolution.

Results - Beam



- DNN applied to events with no neutron information improves on TDR resolution.
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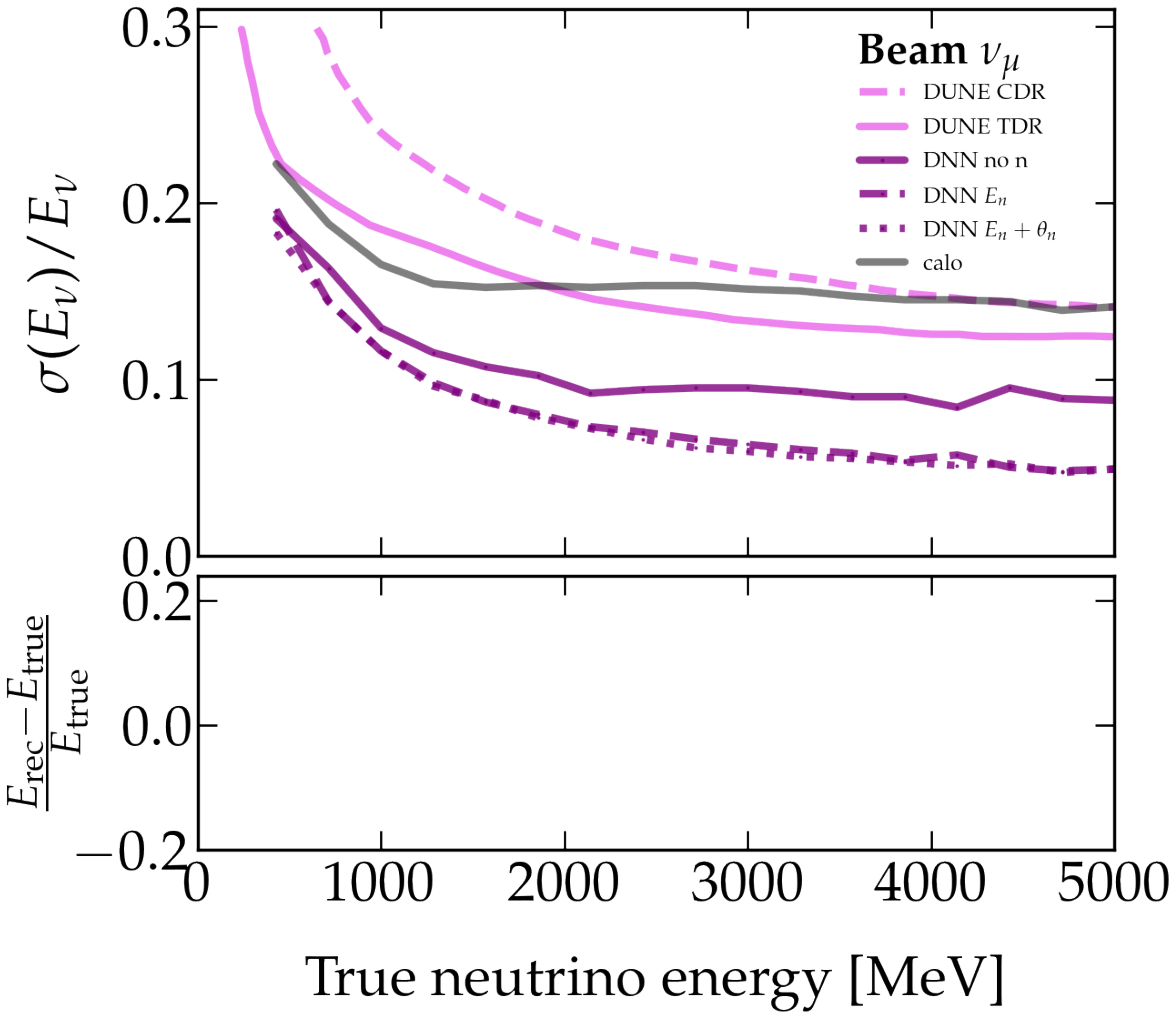

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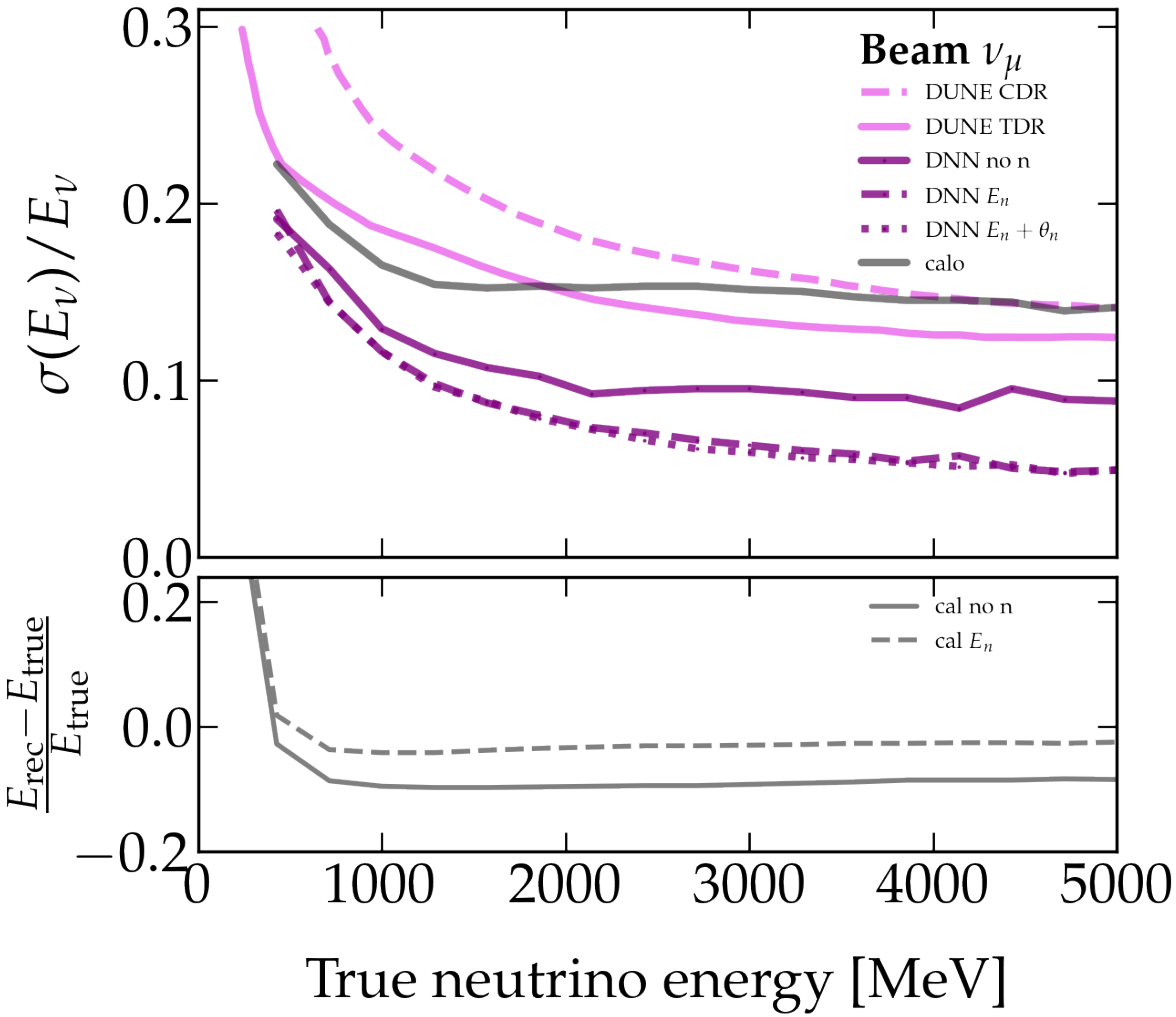

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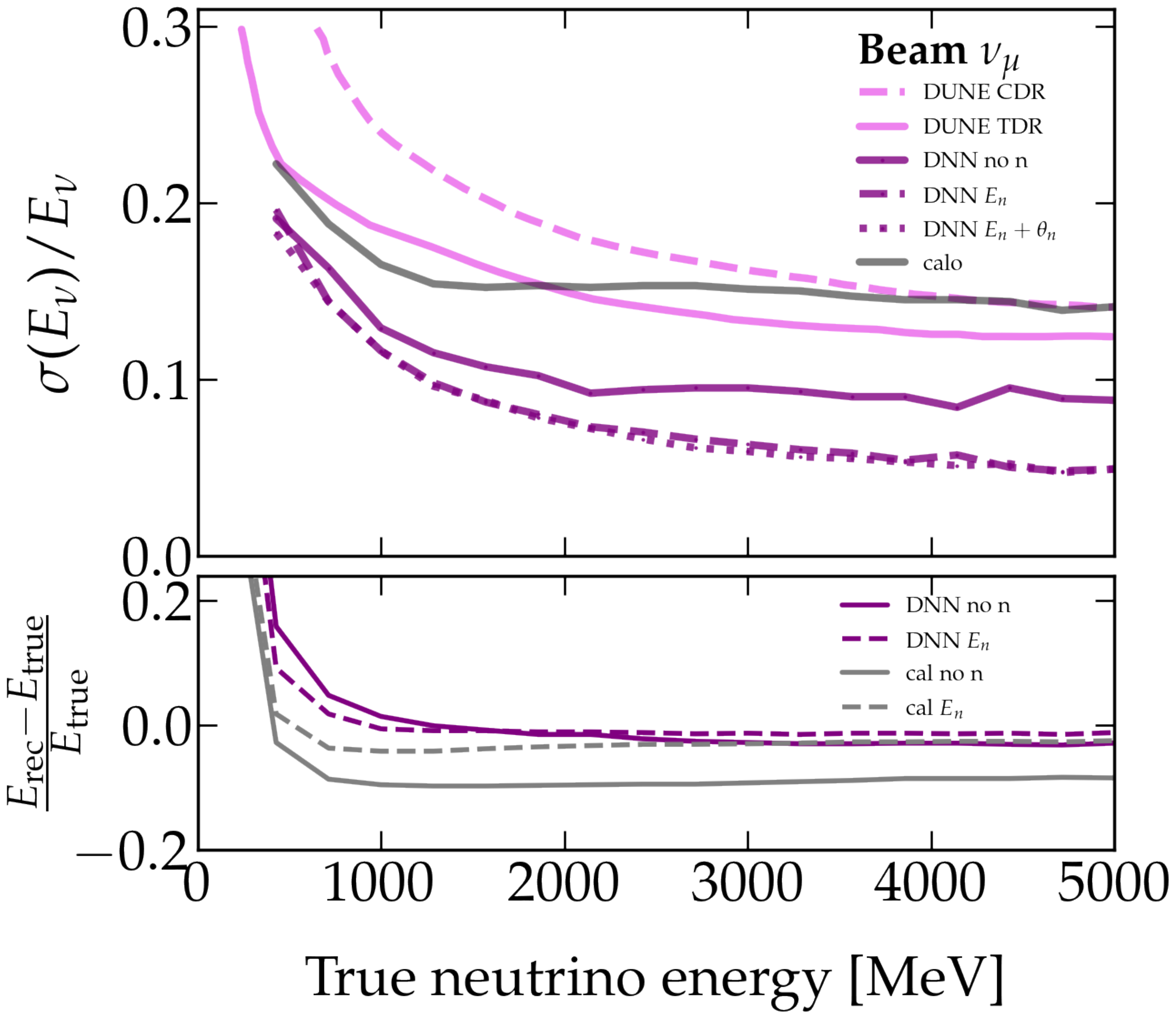

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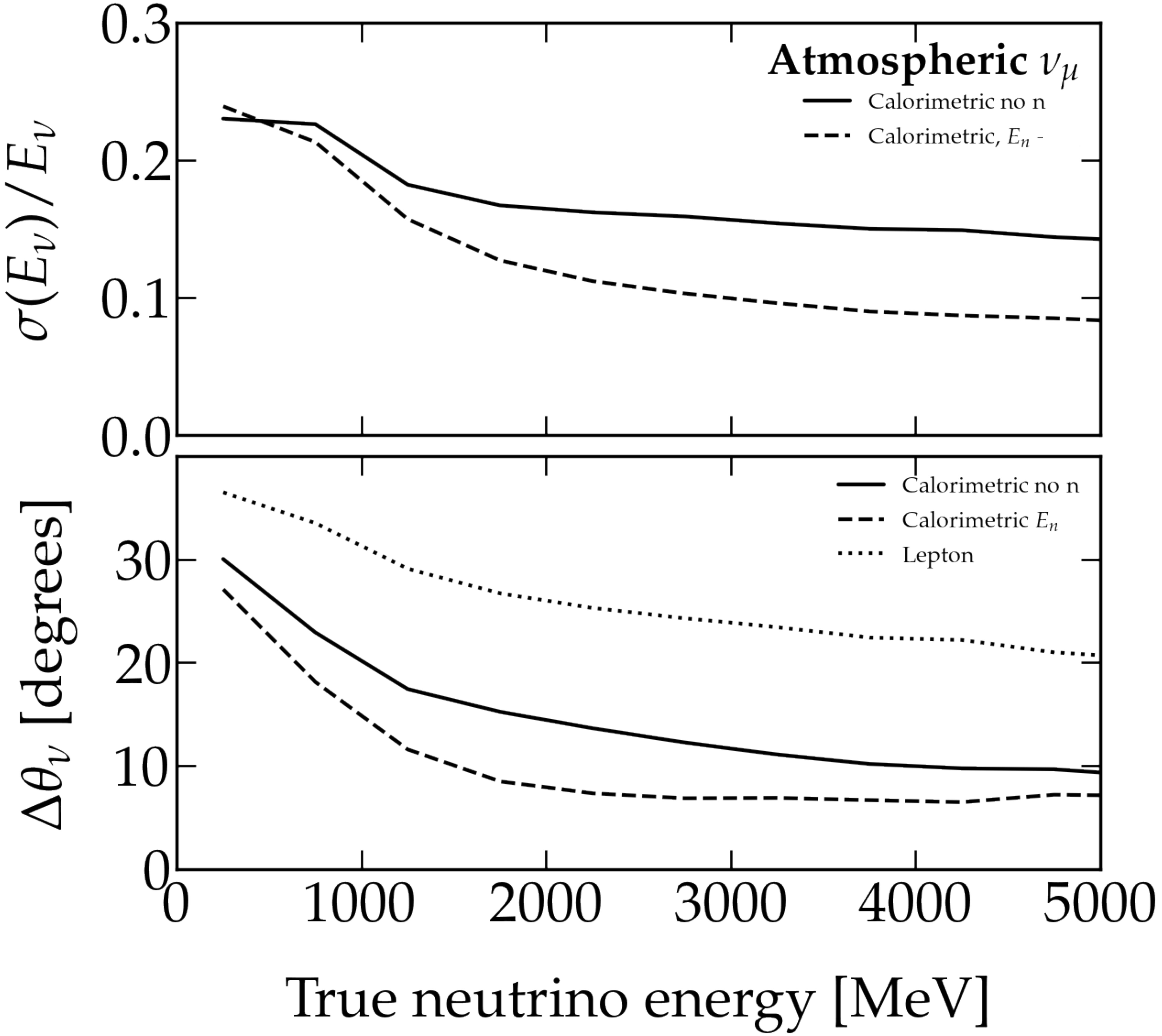
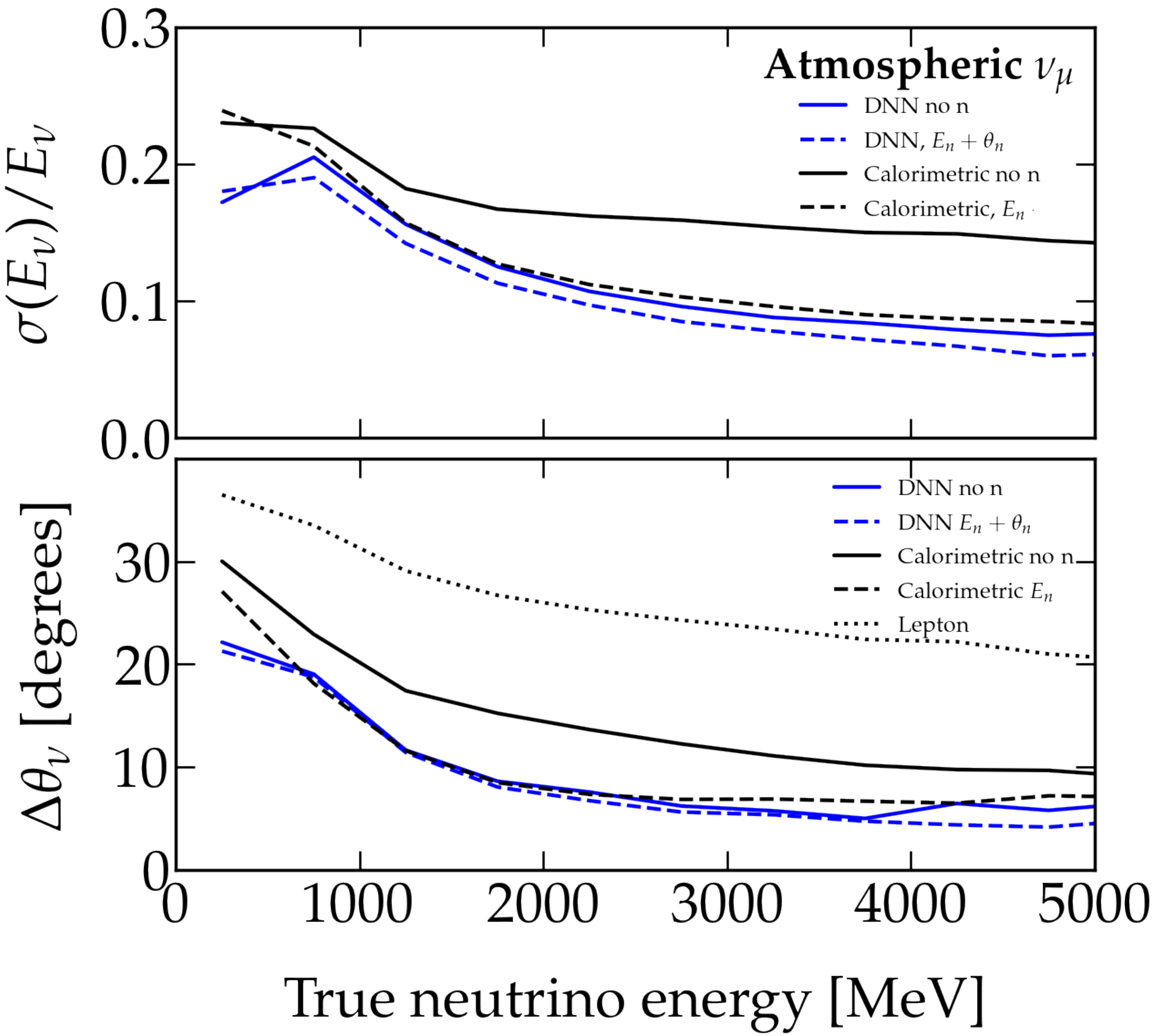
- Adding highly smeared neutron energy information gives 1.5x increase in resolution.
- Having access to full neutron momentum has little impact on network performance.
- DNN has smaller bias than calorimetric method for no neutron case. Both methods perform well when neutron energy is provided.

Results - Atmospherics



- Calorimetric gives reasonable energy and angular resolution.

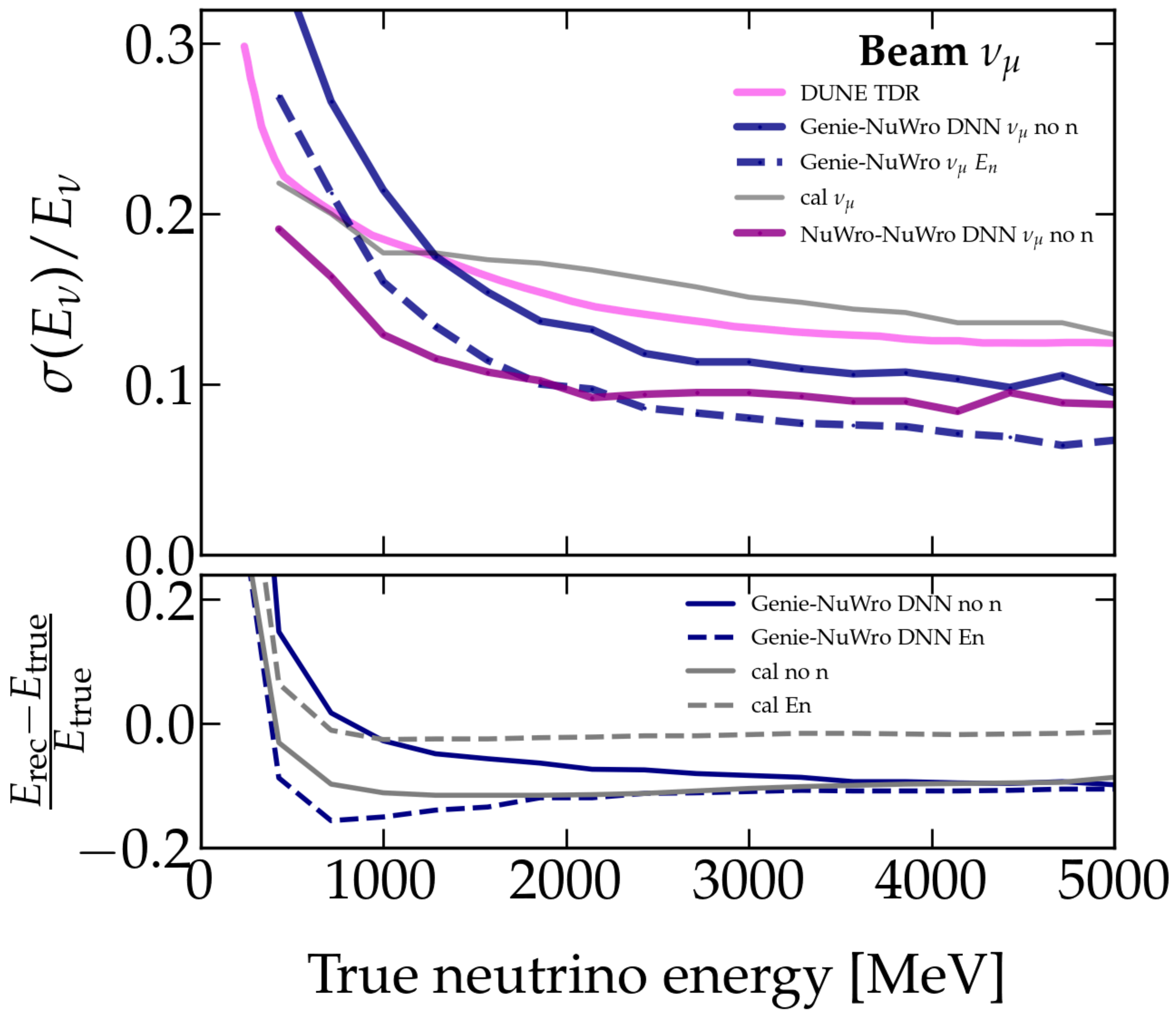
Results - Atmospherics



- Best energy(angle) resolution goes from 15%(9%)→7%(6%) in no neutron DNN case.
- Adding neutron momentum information yields little improvement or network performance.

Neutrino nucleus modelling dependence

- Different event generators use different models → discrepancies in final state particles
- Attempt to reduce model dependence of network by grouping particle types.
- Find network still performs well at higher energies, but isn't robust below 1.5 GeV.



Sensitivities (PRELIMINARY)

Sensitivities assuming 624 kt-MW-years of exposure: 6.5 years each of running in neutrino (FHC) and antineutrino (RHC) mode
40-kt fiducial mass far detector, in an 120-GeV, 1.2 MW beam.

θ_{12}= 0.58678 ± 0.014 ,θ_{13} = 0.149 ± 0.0236 θ_{23}= 0.823795 Δm^2_{12}= 7.4e-05 ± 2.1e-06 Δm^2_{13}= 0.002494 $\delta_{CP} = -\pi/2$

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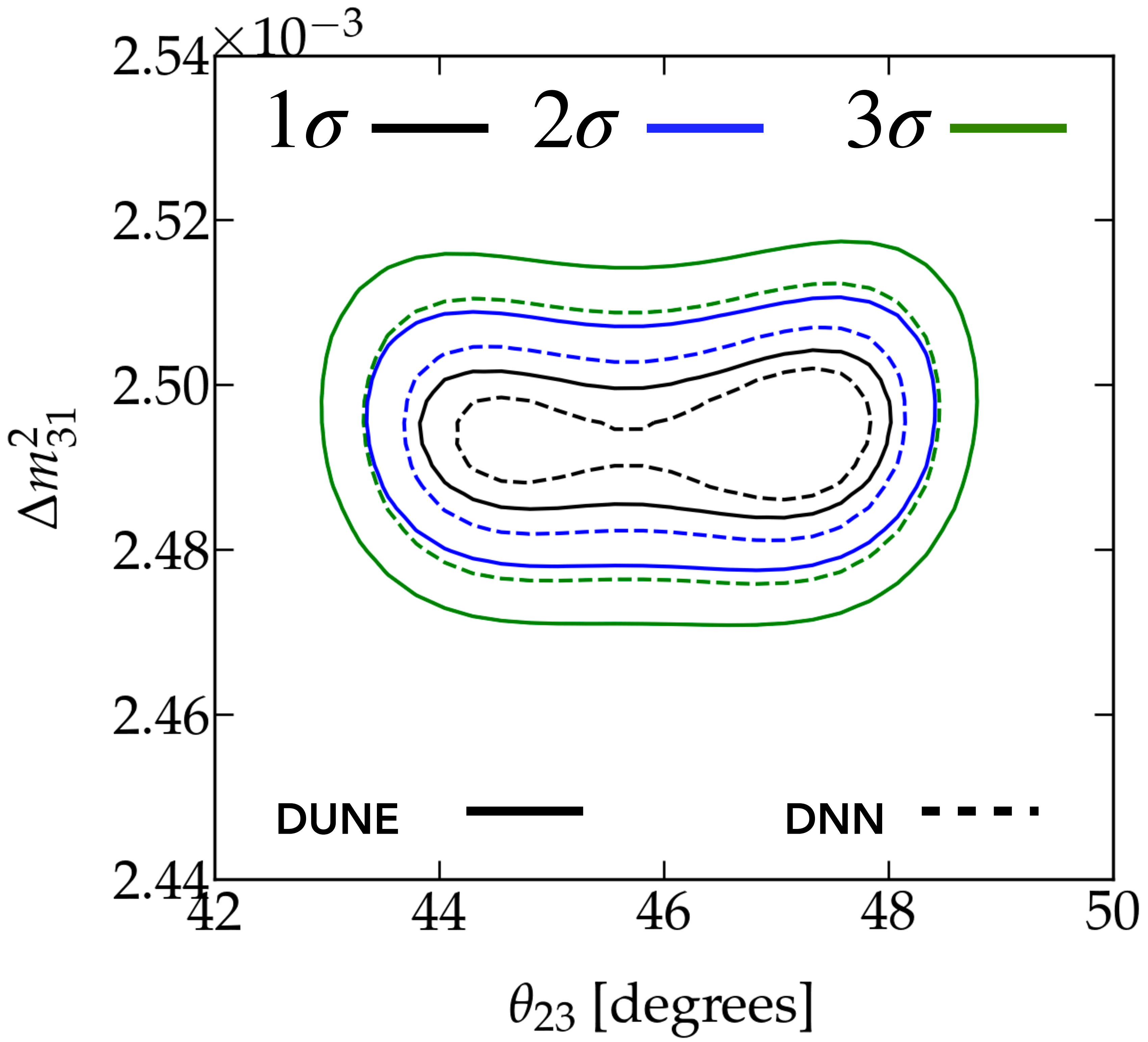

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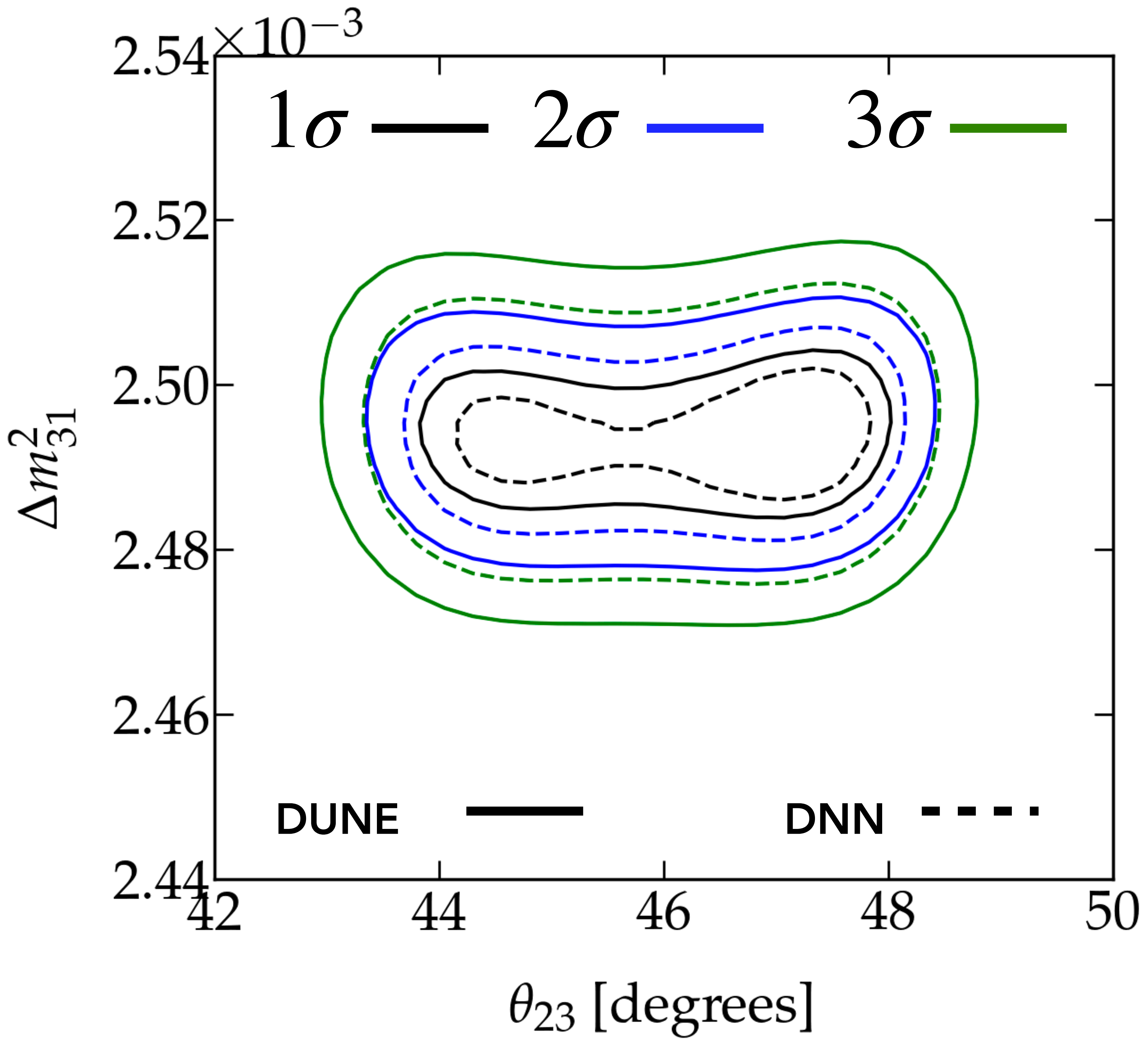

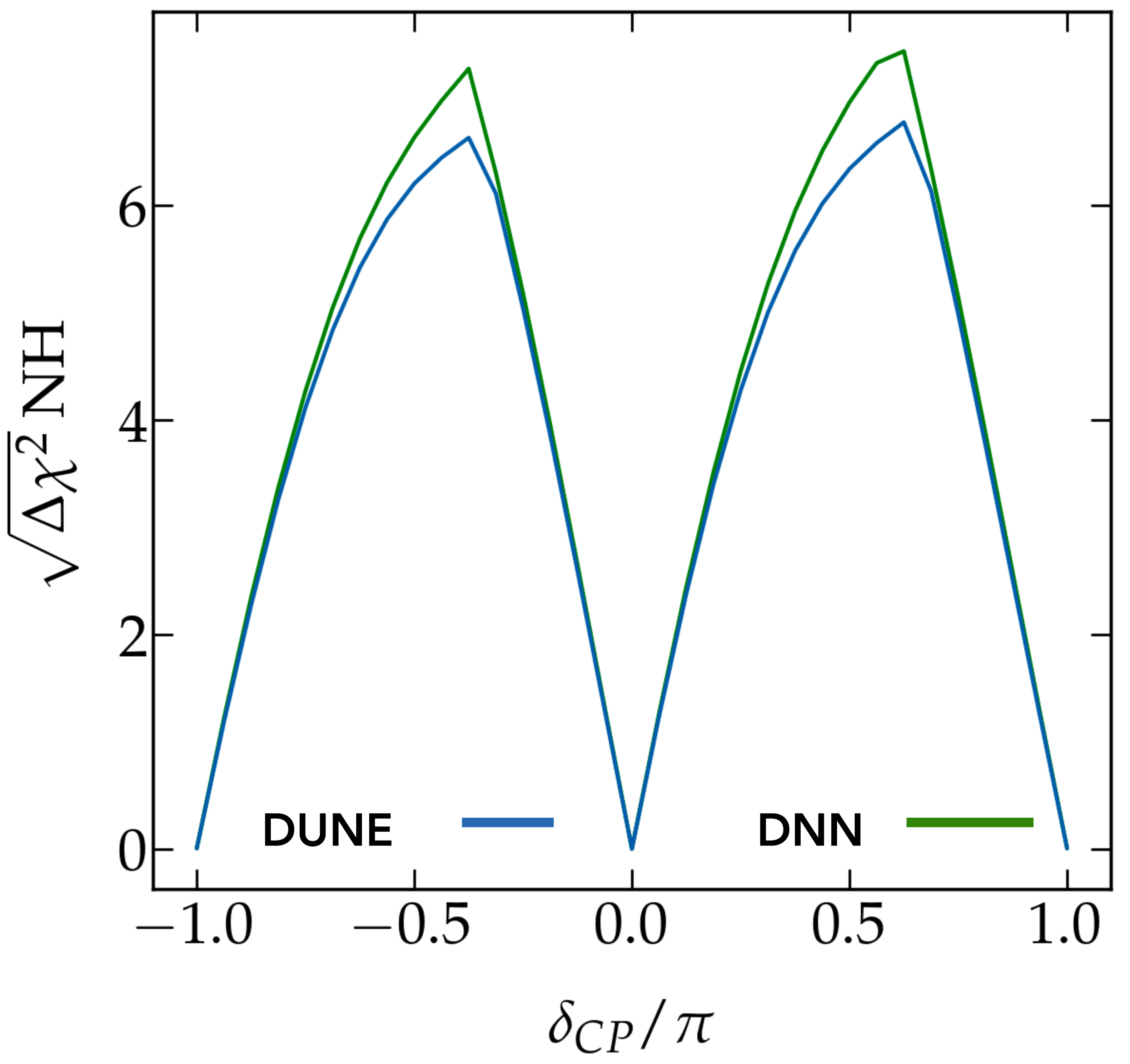

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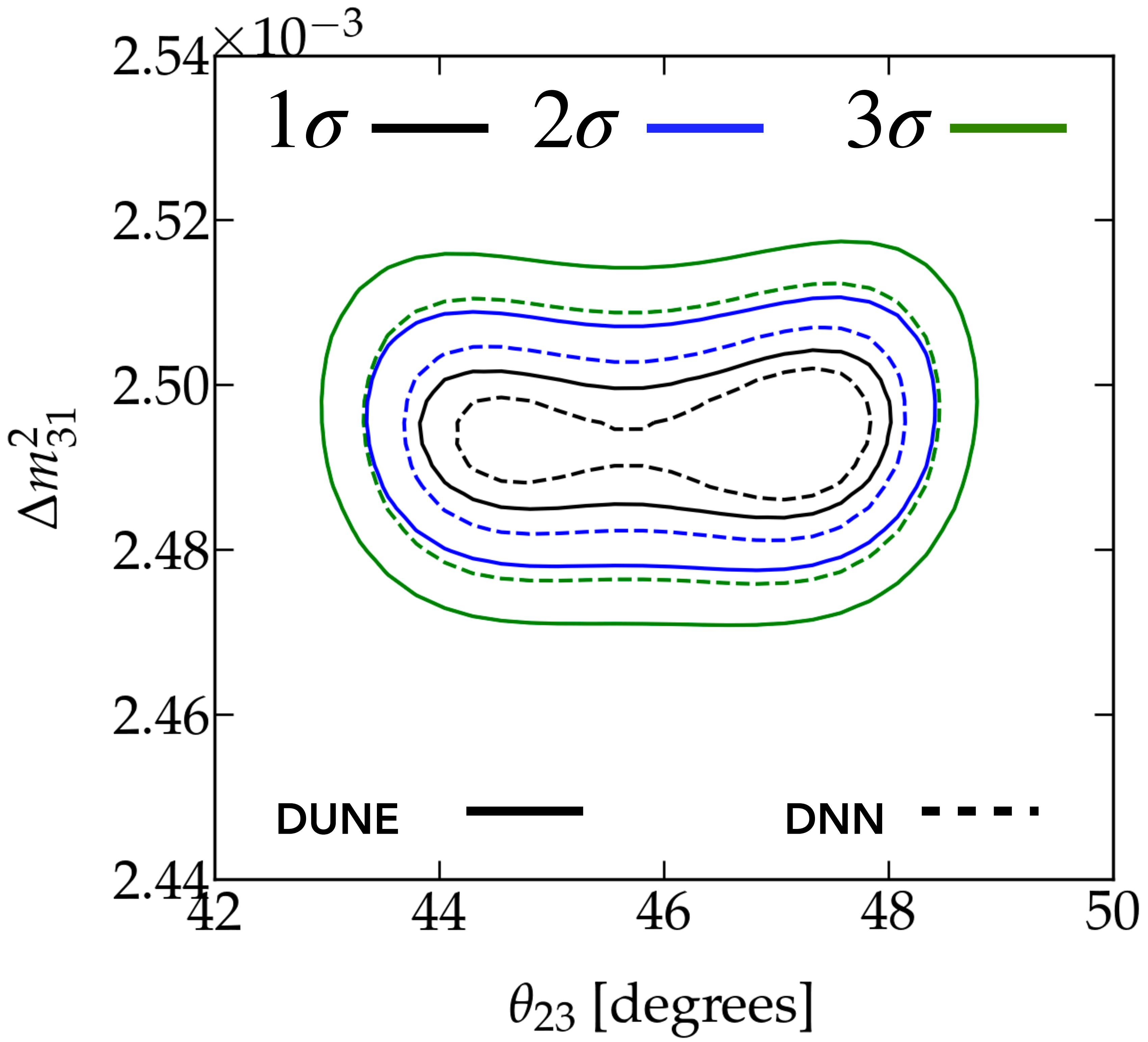

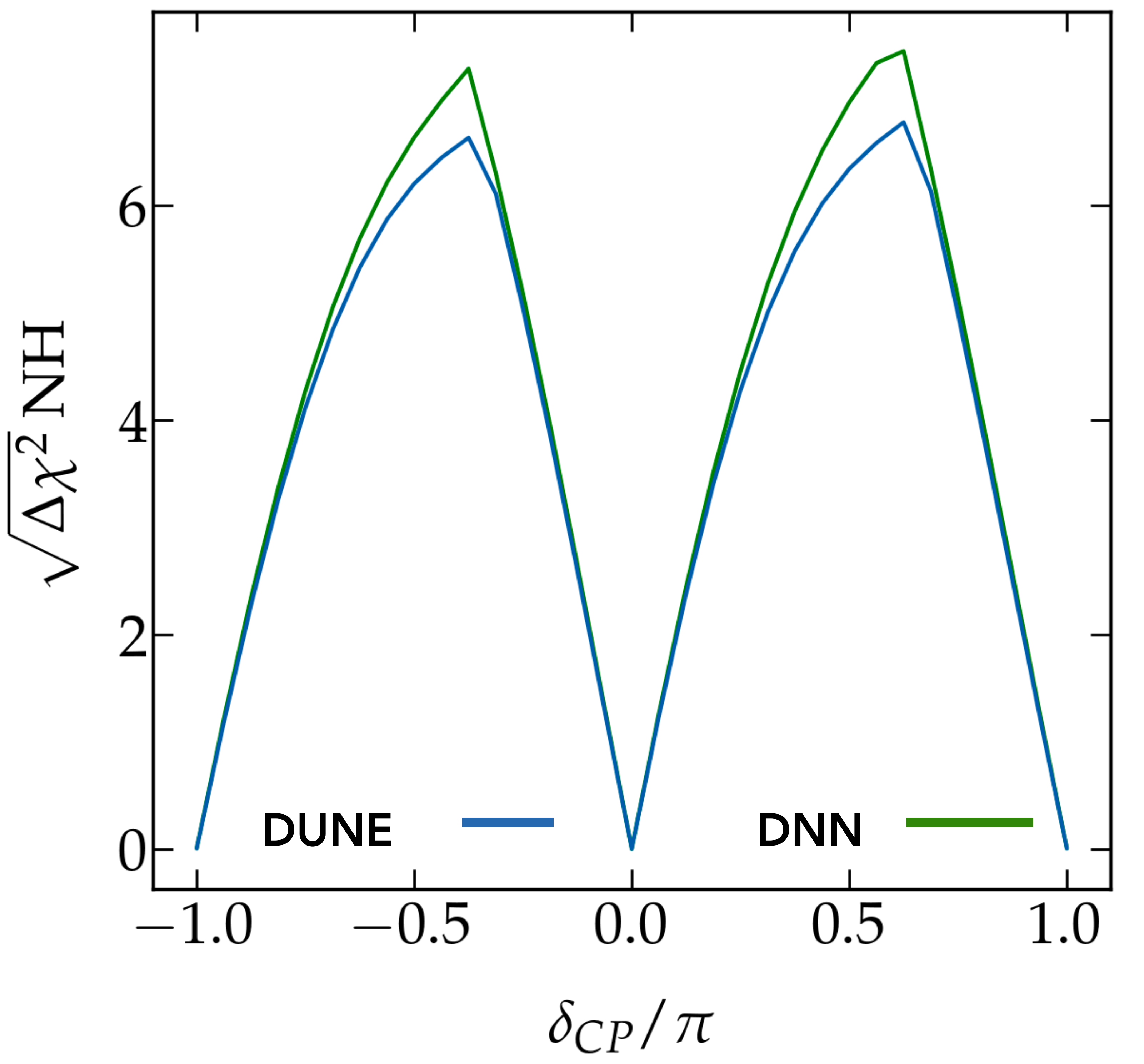

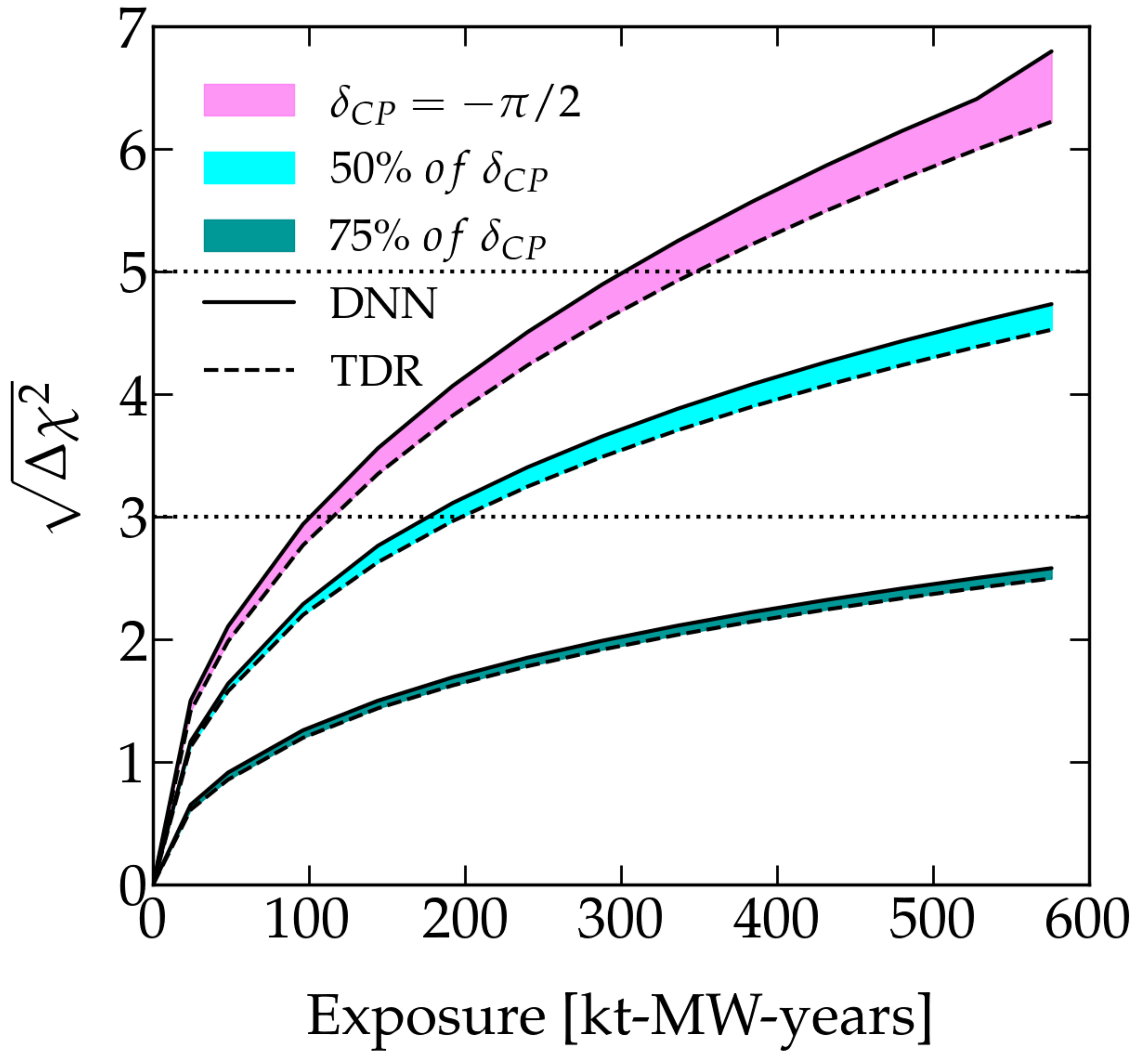

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Conclusions

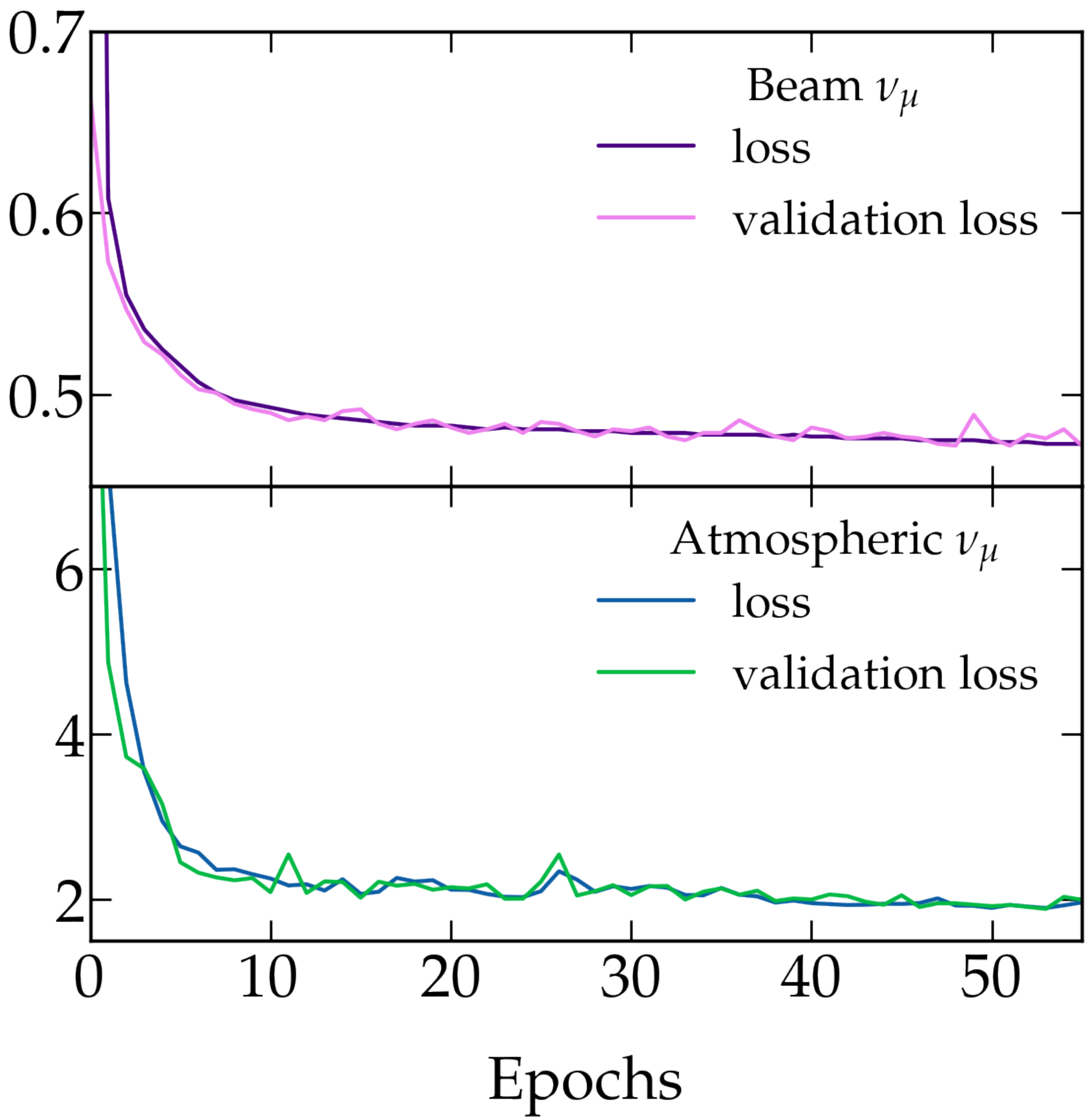
Applying Deep Neural Network to final state particle information can significantly improve energy and angular resolution in LArTPCs

Network has some generator dependence due to neutrino interaction modelling differences, but can still make improvements at higher energies.

Greatest gains made on Δm^2_{31}

Could lead to an improvement in δ_{cp} sensitivity at DUNE, and a quicker achievement of a 5σ measurement!

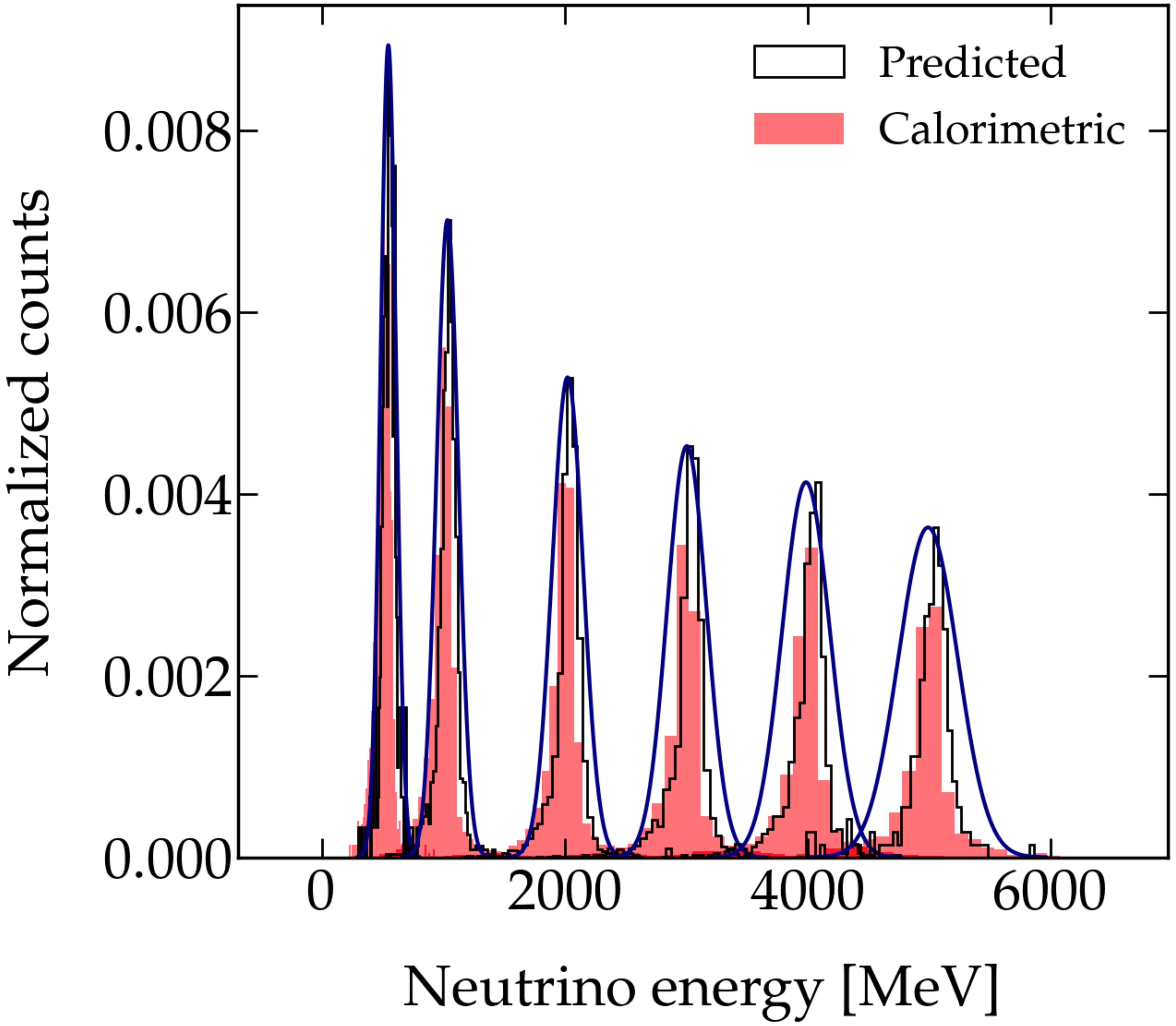
Backups - loss plots



Label events with true neutrino energy

Label events with true neutrino energy and direction

Backups - Energy distributions



Normalize by area of histogram
Add gaussians to legend
Make gaussians make more sense

Smearing table

Particle	Minimum K.E.	Angular Uncertainty	Energy Uncertainty
Proton	30 MeV	10°	10%
Pion \ Kaon	30 MeV	10°	10%
Neutron	30 MeV	10°	40%
Λ	30 MeV	10°	10%
$\mu^{\pm}$	5 MeV	2°	5%
$e^{\pm}$	10 MeV	2°	5%

Anti-neutrinos